New search strategies for well tempered neutralino dark matter

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University of Oregon

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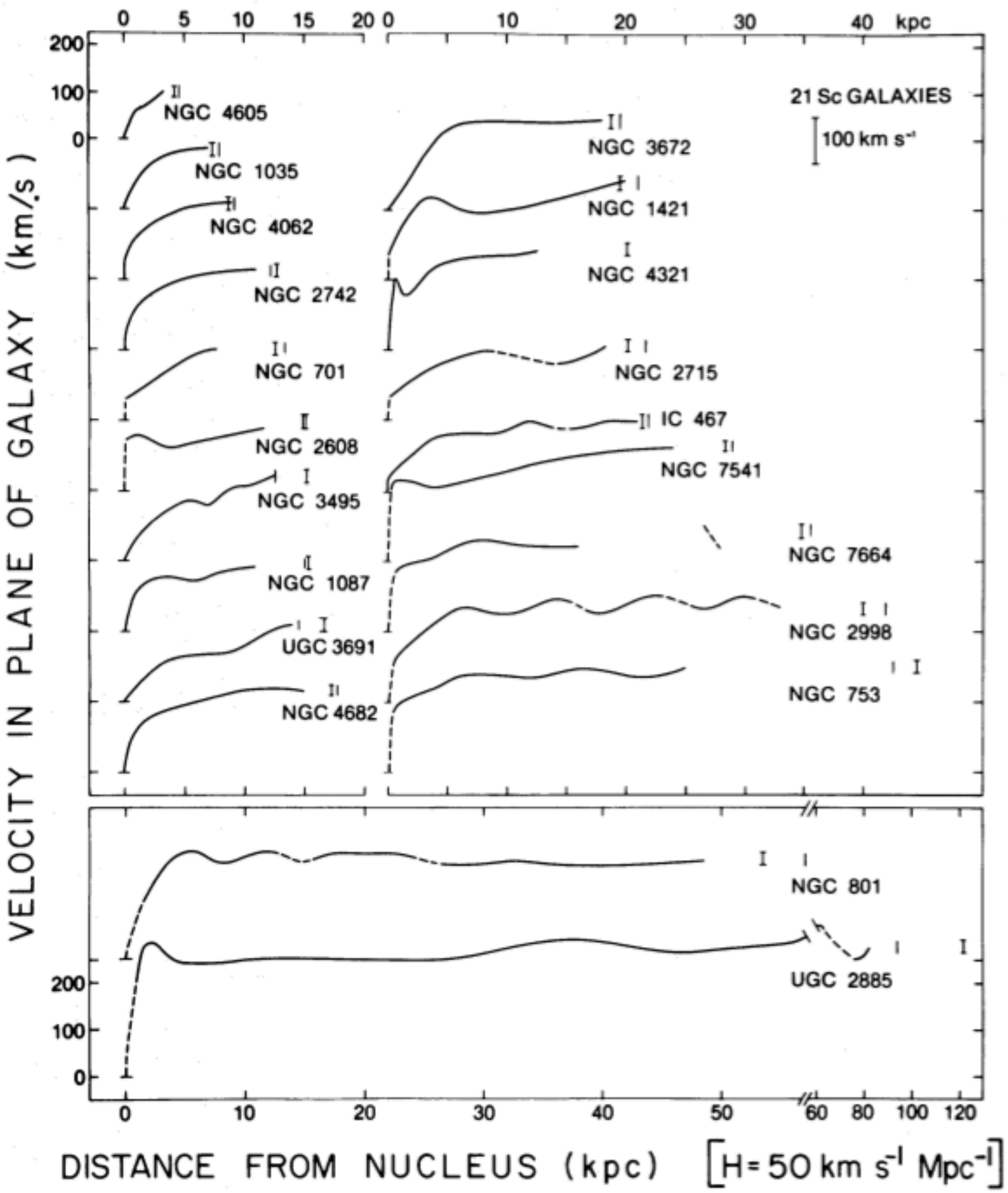
Roadmap of the talk

- Briefly review WIMP dark matter
- Explain what a well tempered neutralino is
- Astrophysical constraints from Indirect/Direct Detection
- Discuss why well tempered neutrinos are hard to find
- Show example of new strategies
- Parameter space covered with strategies

Dark Matter Overview



Evidence for DM

- Rotation curves
- Gravitational lensing
- Ia supernovae
- Cosmological nucleosynthesis
- CMB anisotropies

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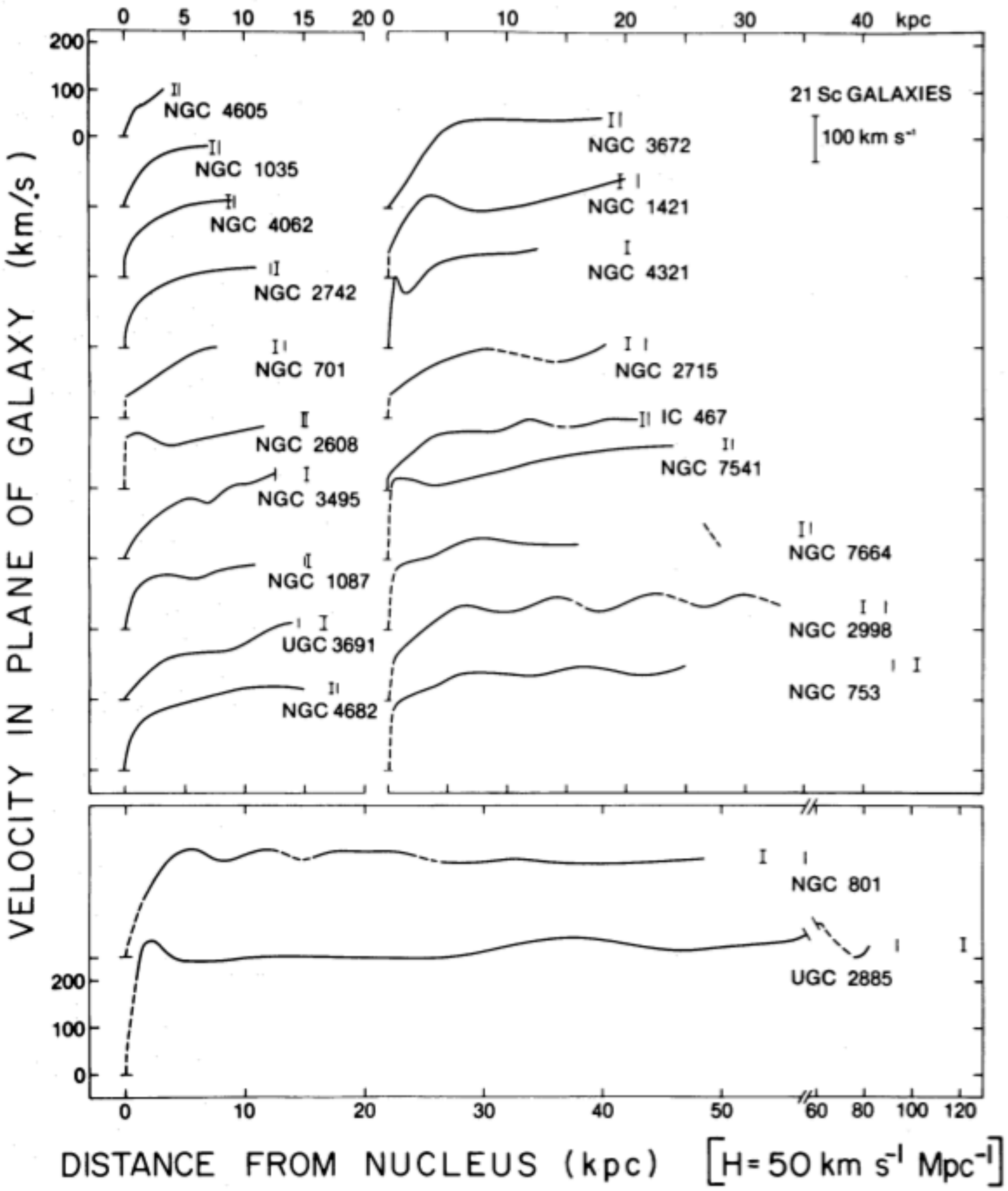

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What do we Know?

- Density

$$\Omega_c = \rho\frac{8\pi G}{3H_0^2} = 0.2568$$

- Interacts with gravity, not photons

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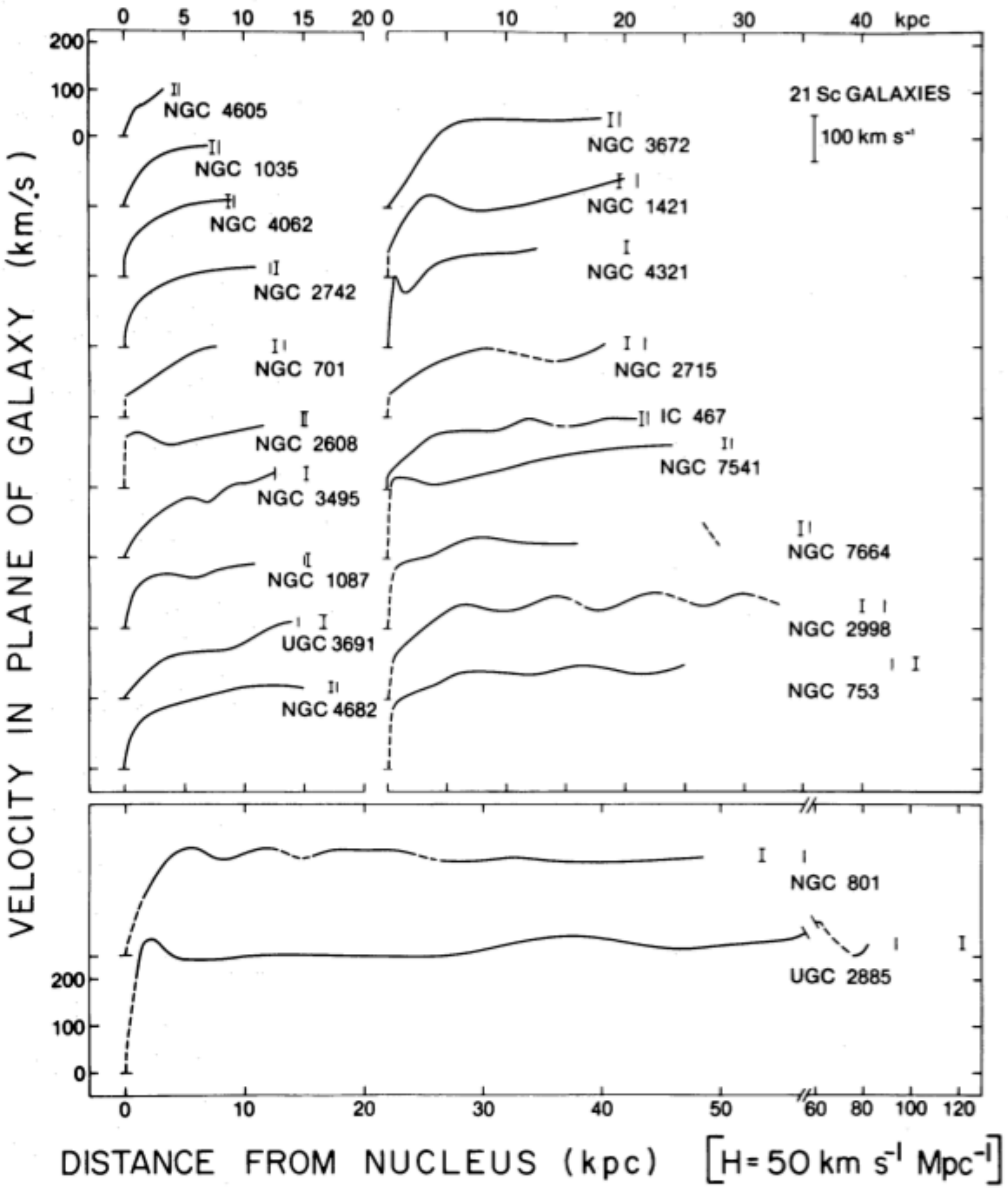

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Still need to know:

- Mass, spin, interactions…

WIMP Dark Matter

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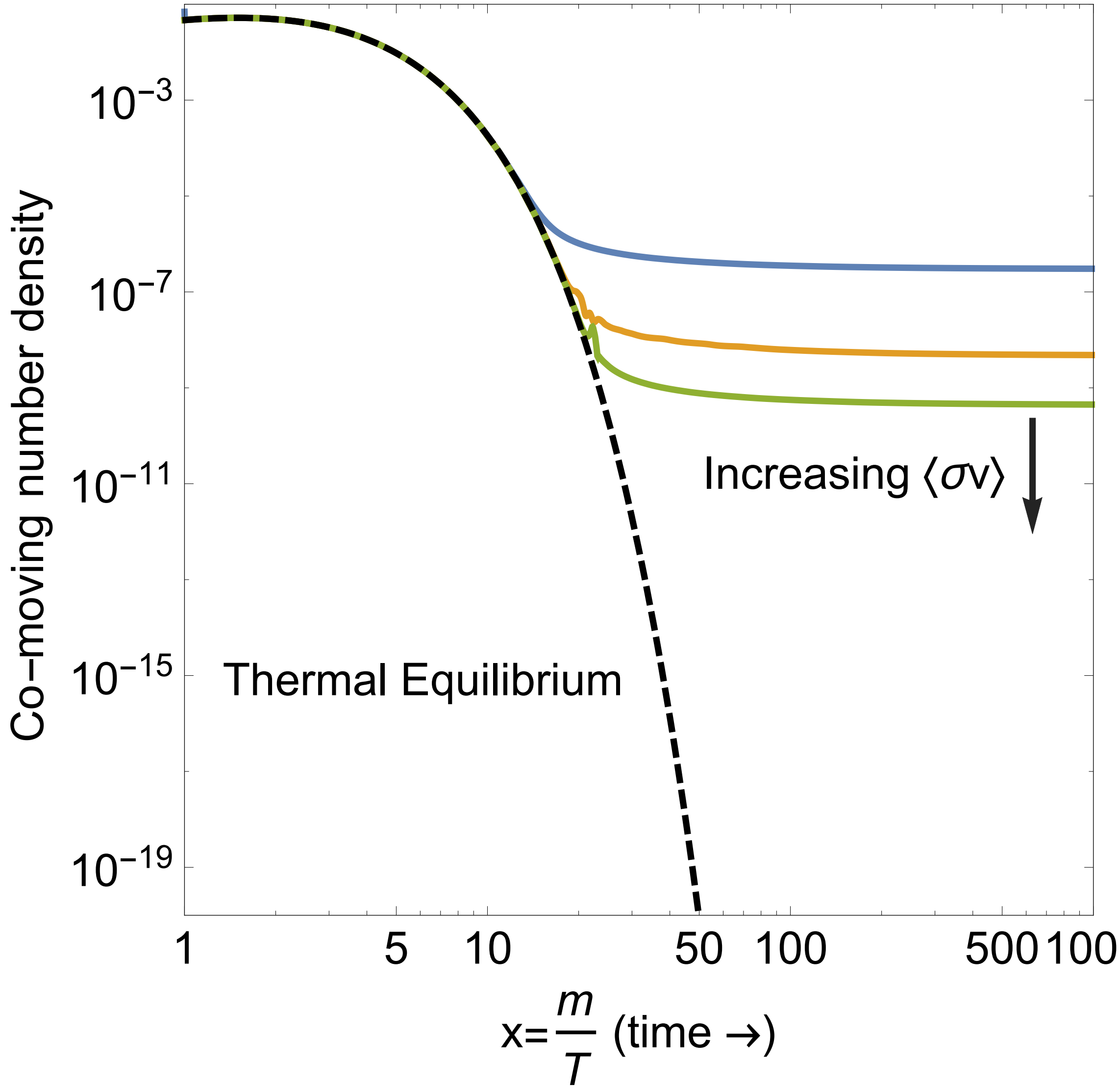

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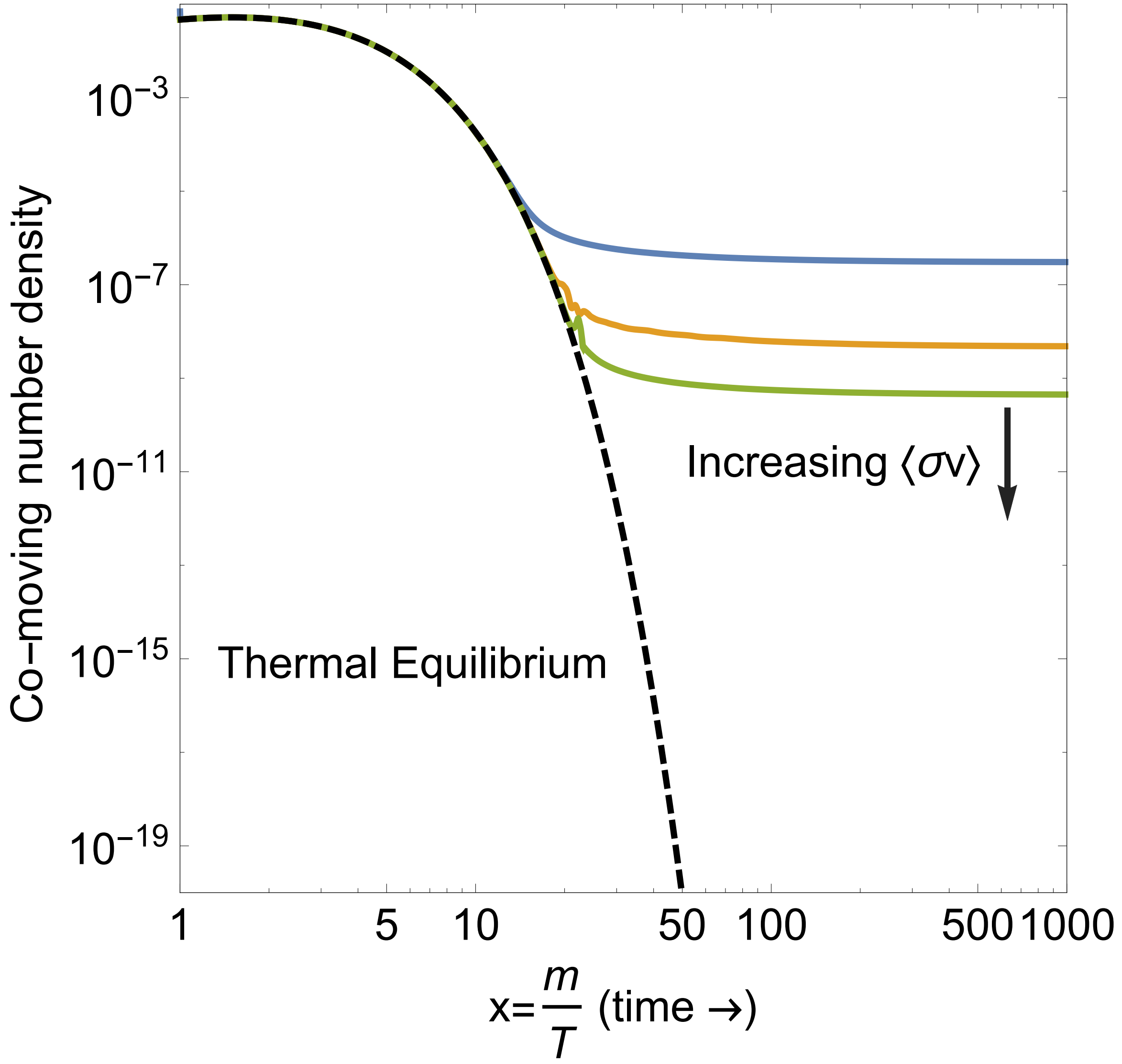
- Allows for search methods
  - Direct Detection
  - Indirect Detection
  - Production at colliders



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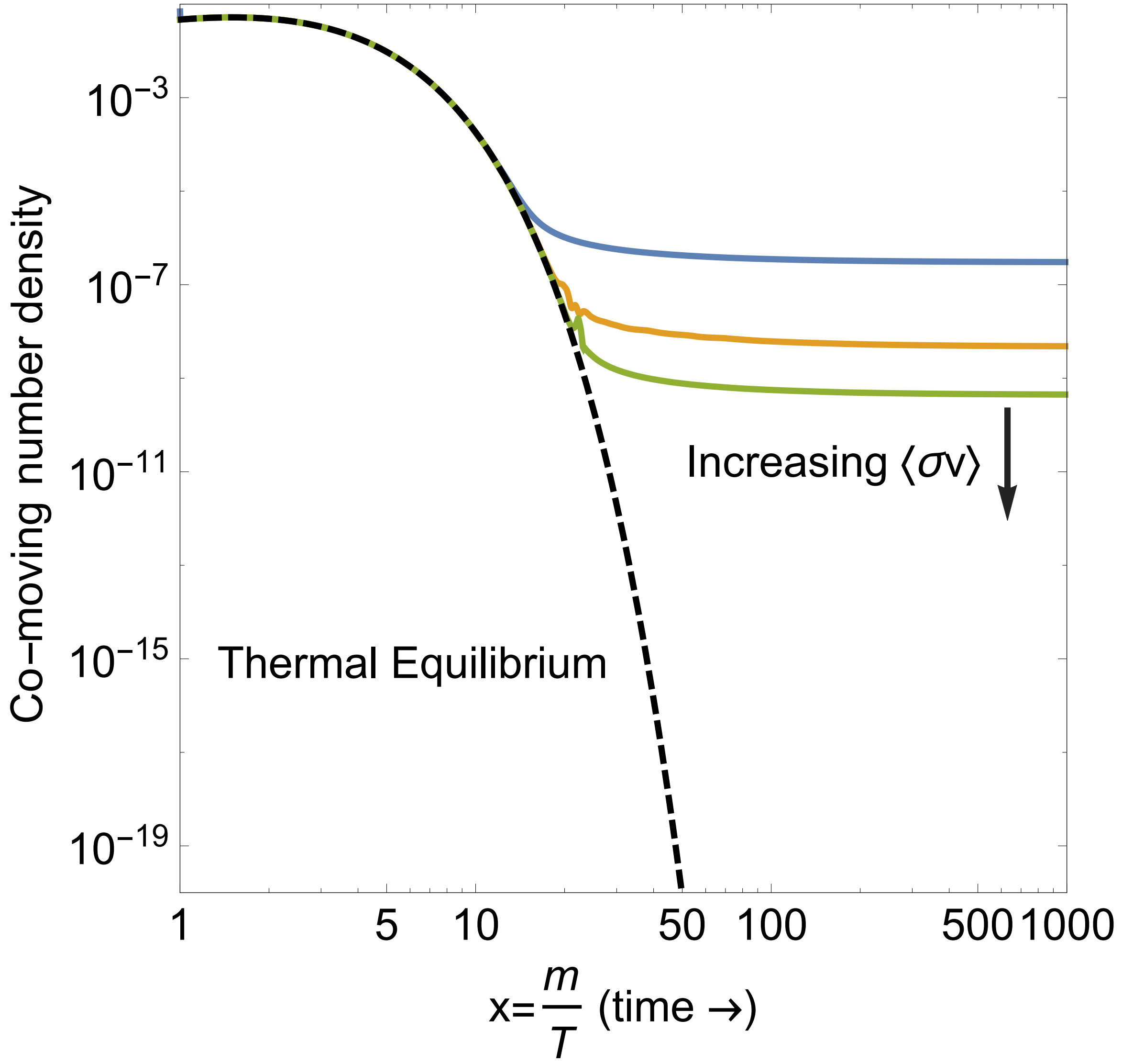

Use supersymmetry as a WIMP model. Extra particles affect $\langle \sigma v \rangle$

Dark matter from supersymmetry

Spin 0	Spin 1/2	Spin 1
h		
	q, l	
		V_μ

Dark matter from supersymmetry

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Higgsinos and Gauginos mix to form Neutralinos and Charginos

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$\langle \sigma v \rangle$ **determined by** $M_1, M_2, \mu, \text{ and } \tan\beta$

R parity doesn't allow LSP to decay

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Isolated EW-inos

What mass is needed to quench relic abundance?

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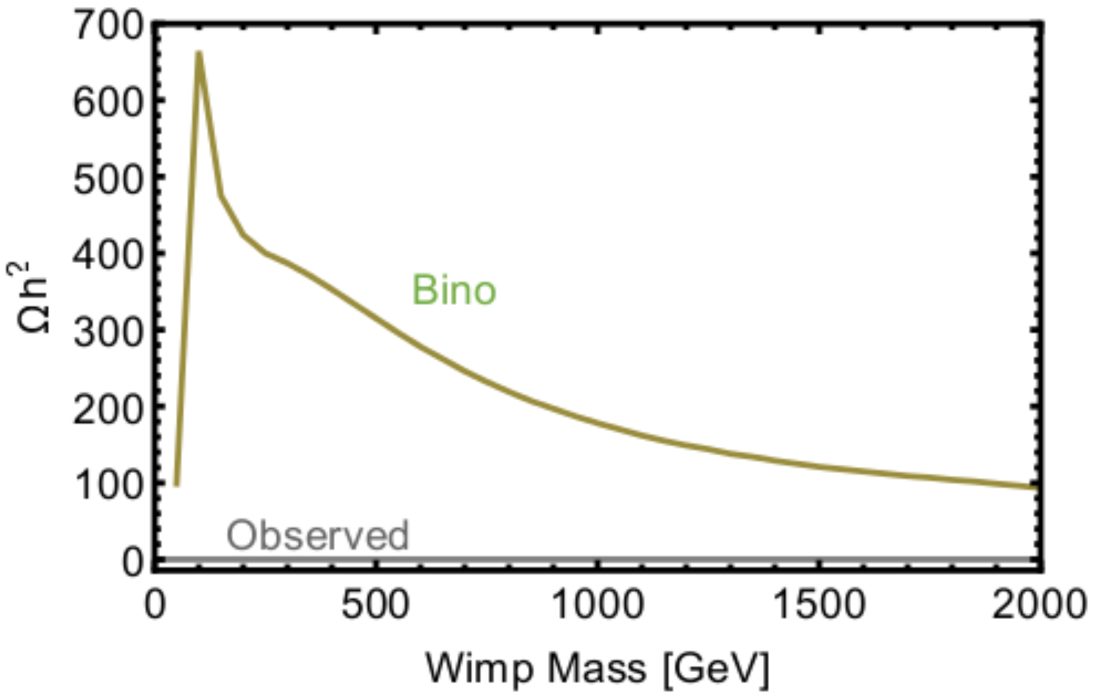
Bino

- Gauge singlet
- 1 Neutralino, 0 Charginos



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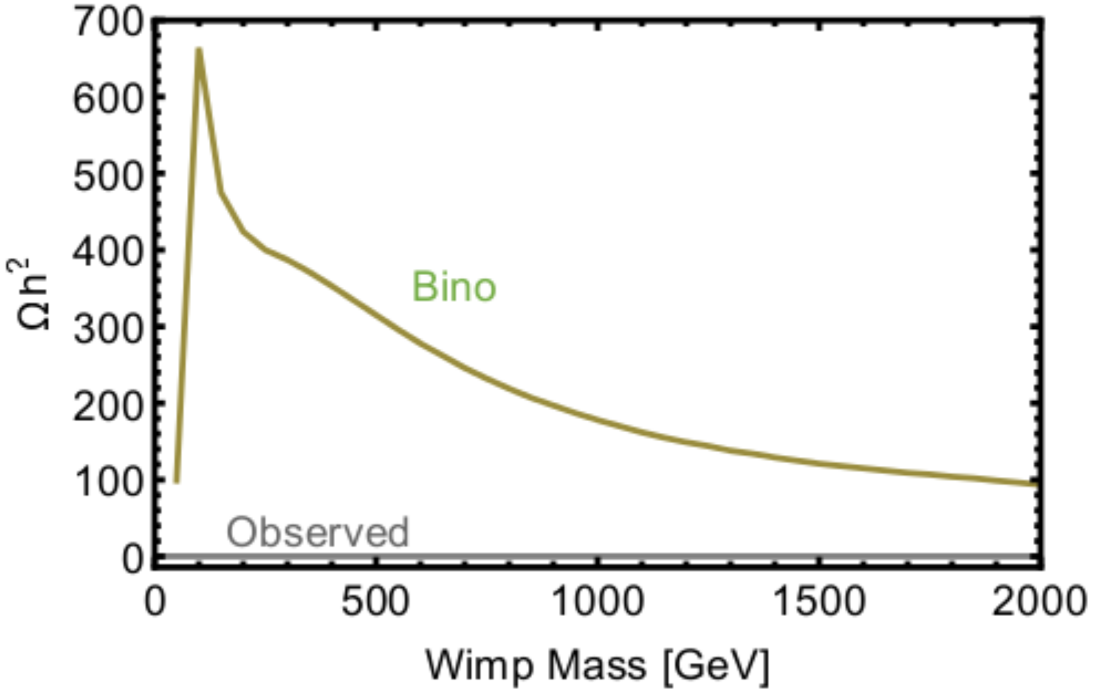
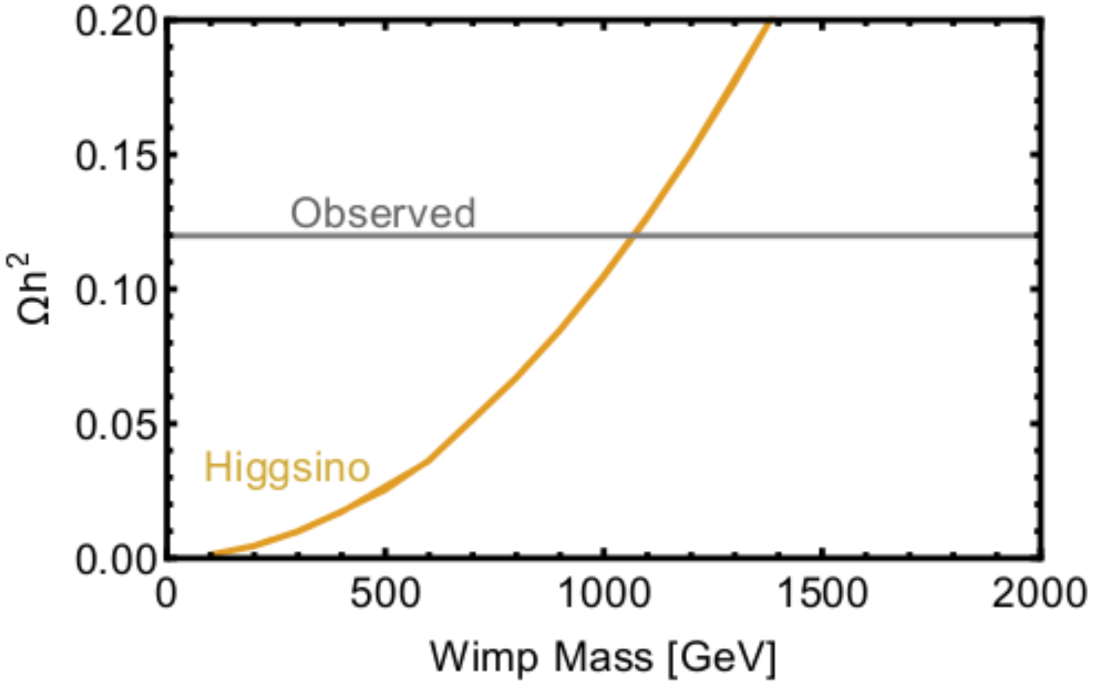


Higgsinos

- 2 Gauge doublets
- 2 Neutralinos, 1 Charginos



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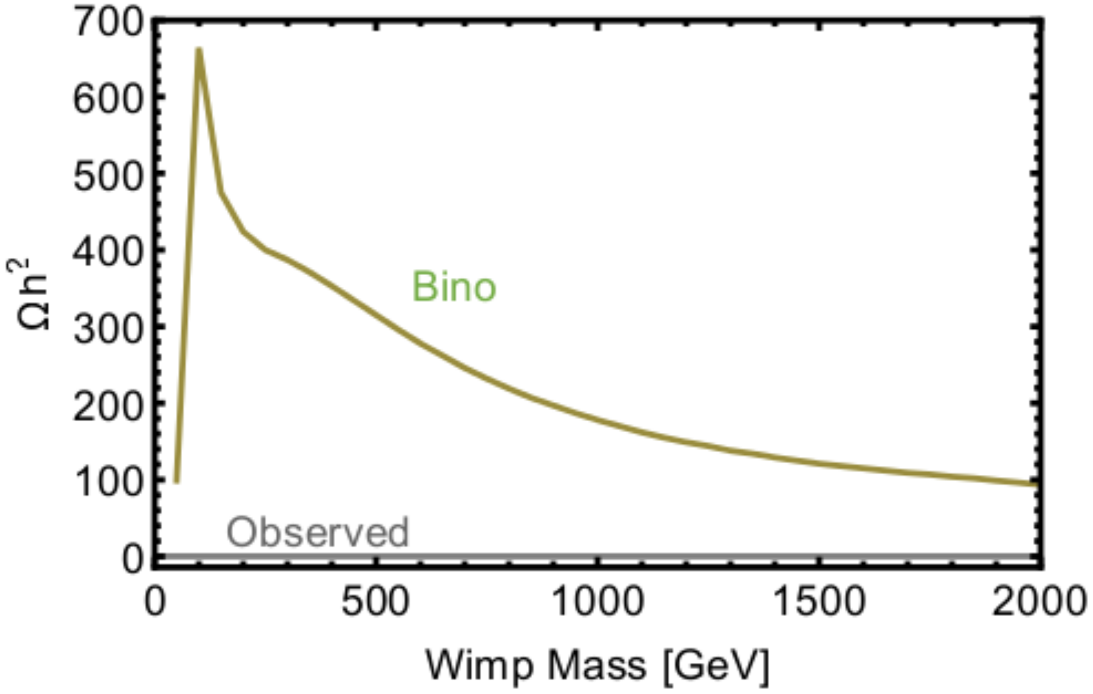

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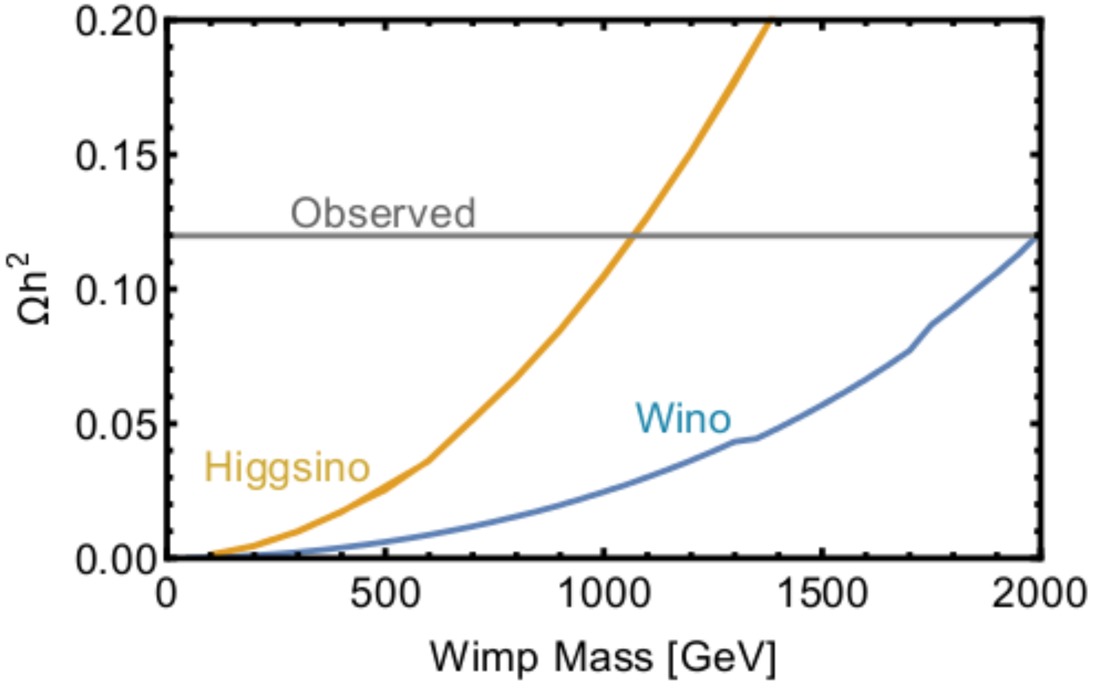

Wino

- 1 Gauge triplet
- 1 Neutralino, 1 Charginos

Co-annihilations

Why are the relic abundances different for the pure electroweakinos?

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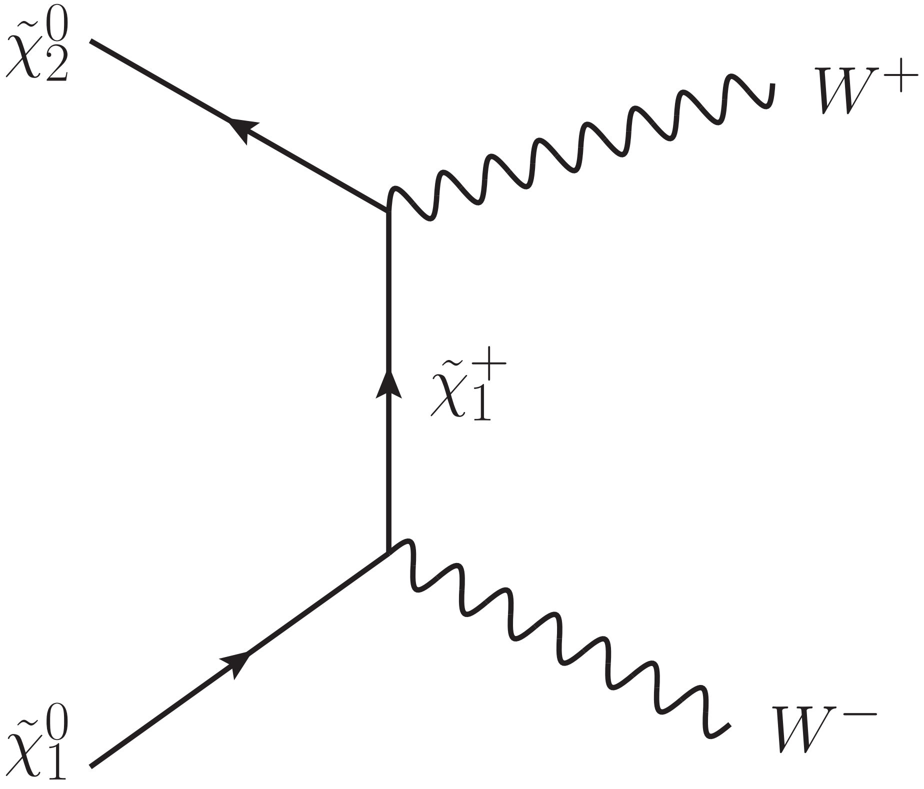

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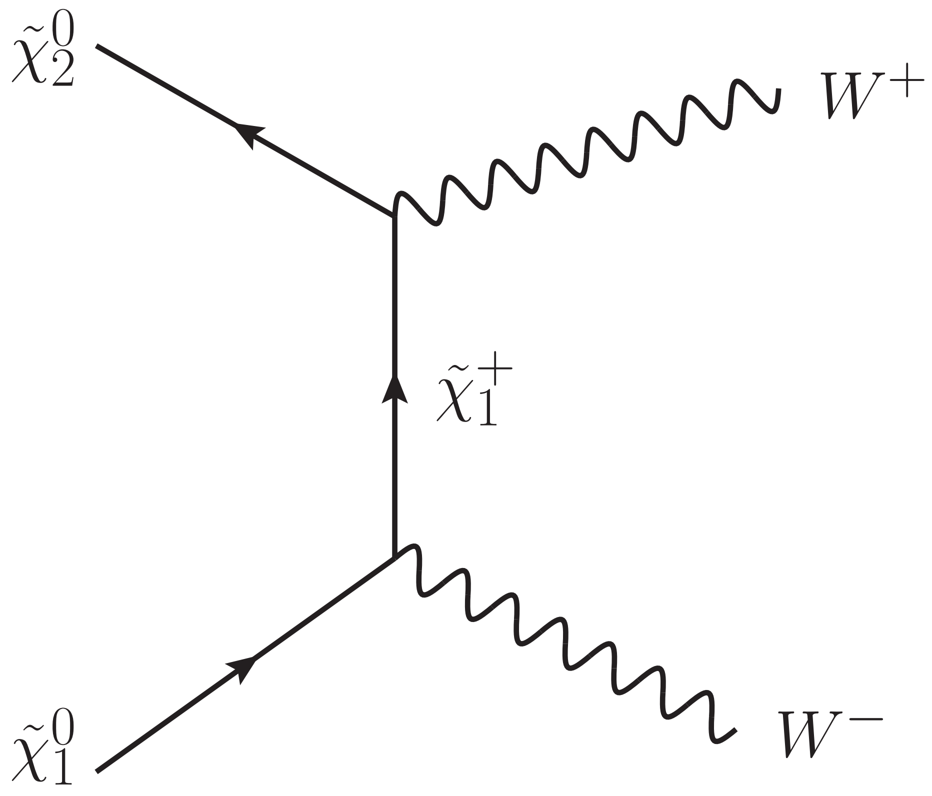

Annihilation cross section affected by particles near in mass

Co-annihilations

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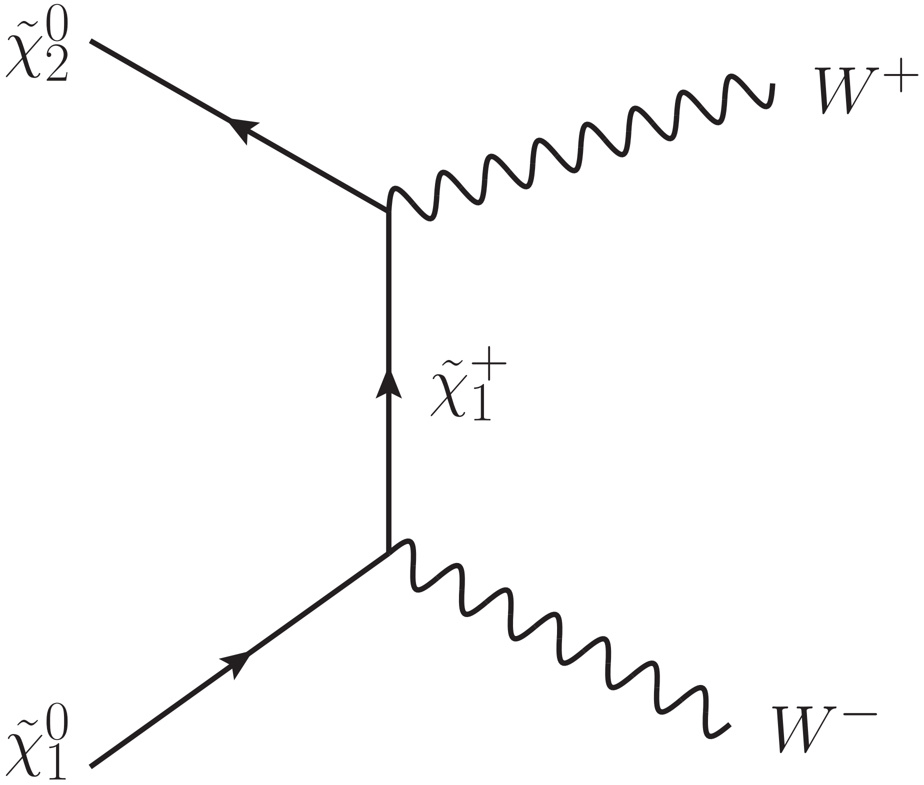


Annihilation cross section affected by particles near in mass

Well Tempering tunes the values of $M_1, M_2, \mu,$ and $\tan\beta$ to achieve observed relic abundance

The Well Tempered Surface

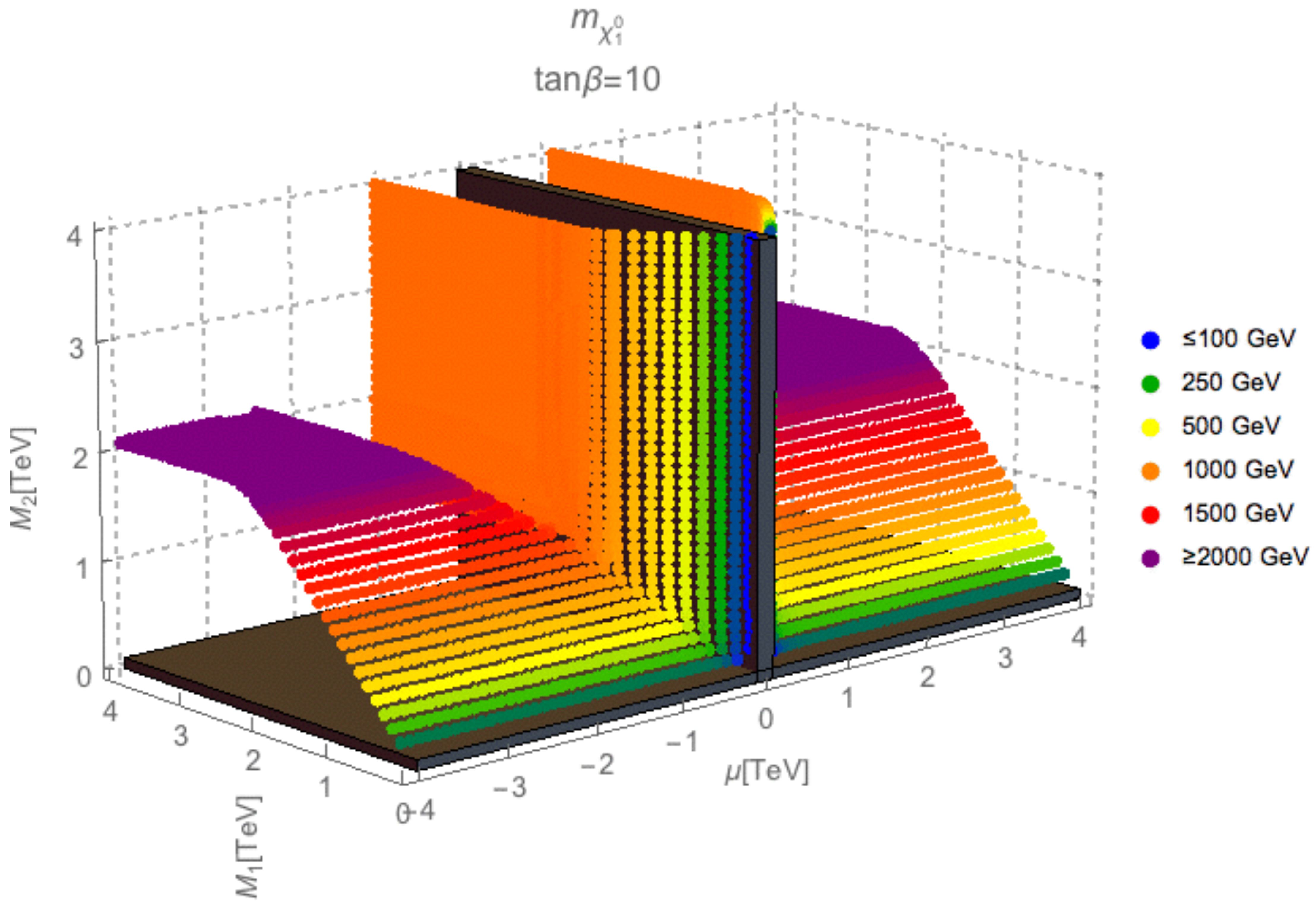
Well Tempering tunes the values of $M_1, M_2, \mu,$ and $\tan\beta$ to achieve observed relic abundance

- Decouple all supersymmetric scalars (heavy Higgs and sfermions)
- Chose a value for tanβ (10)
- Scan over values of M_1, M_2, and μ
  (Spectrum calculated with SUSPECT)
- Keep model point if $\Omega h^2 = 0.12$
  (DM properties calculated with micrOMEGAs)
- Points left over define the **Well Tempered Surface**

Next set of plots were first presented in J. Bramante, P. J. Fox, A. Martin, BO, T. Plehn, T. Schell and M. Takeuchi, "Relic neutralino surface at a 100 TeV collider," Phys. Rev. D 91, no. 5, 054015 (2015) [arXiv:1412.4789 [hep-ph]]

The Well Tempered Surface

Mass of the lightest neutralino



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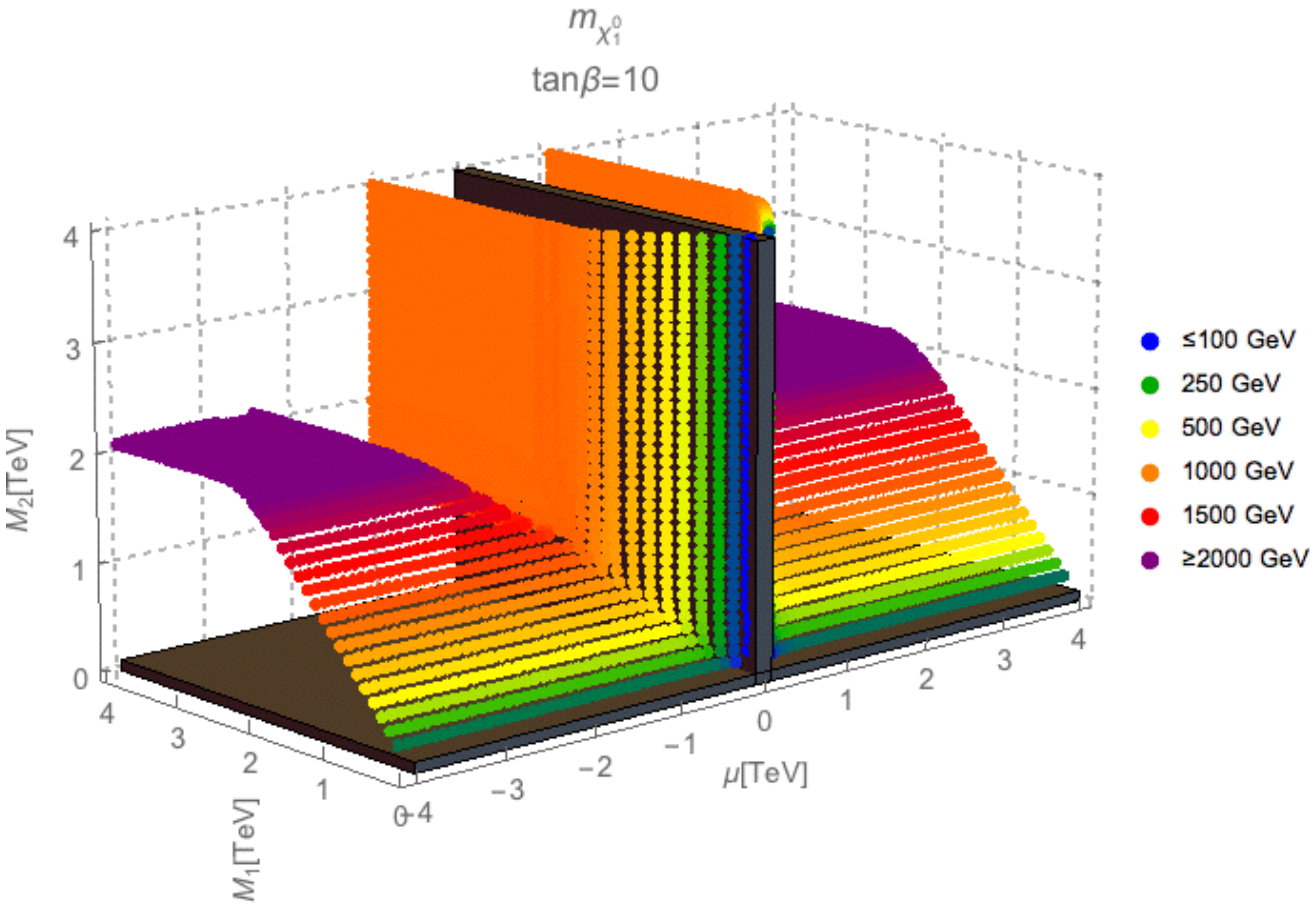
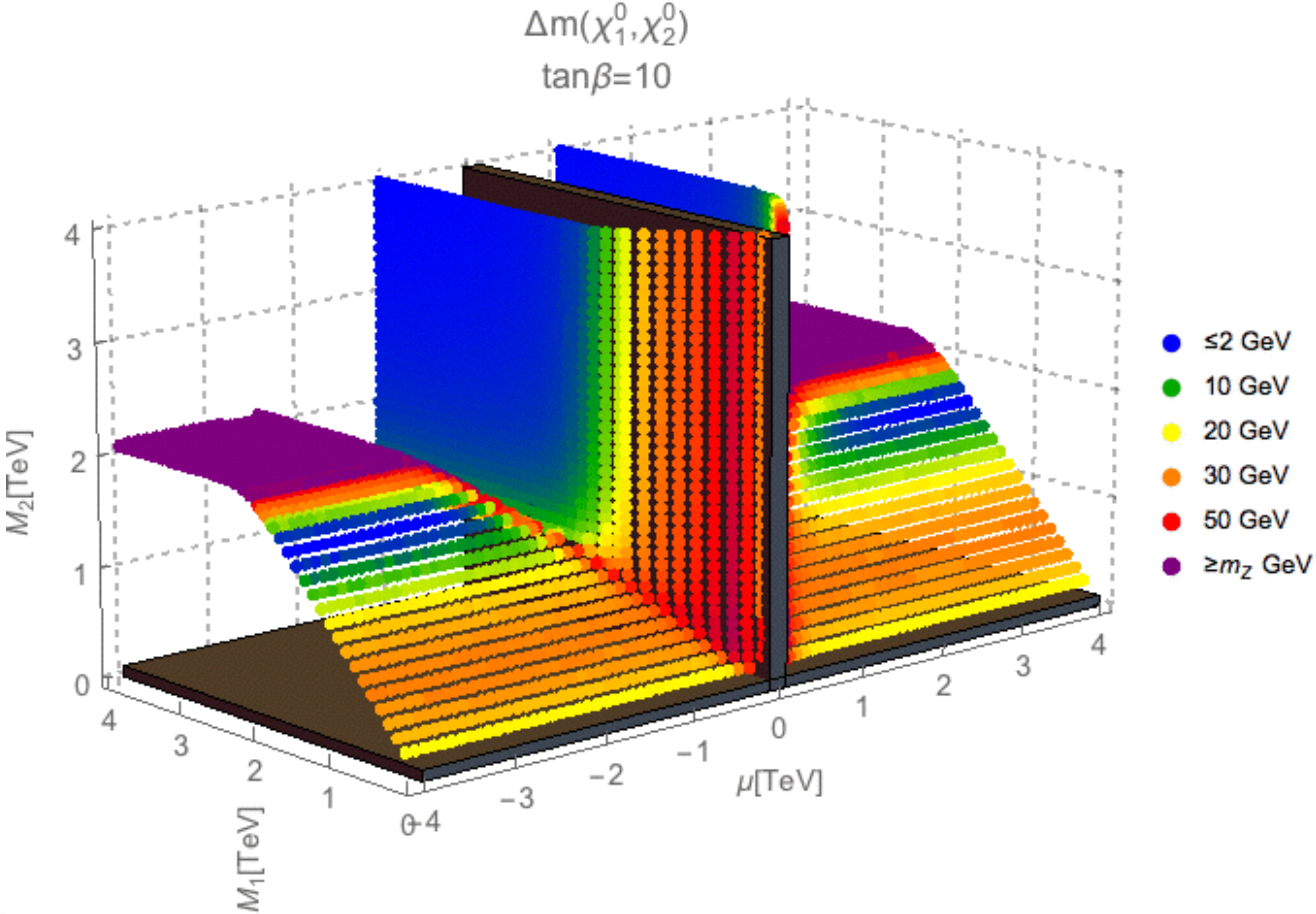
Mass of the lightest neutralino



The Well Tempered Surface

Mass difference between the lightest two neutralinos



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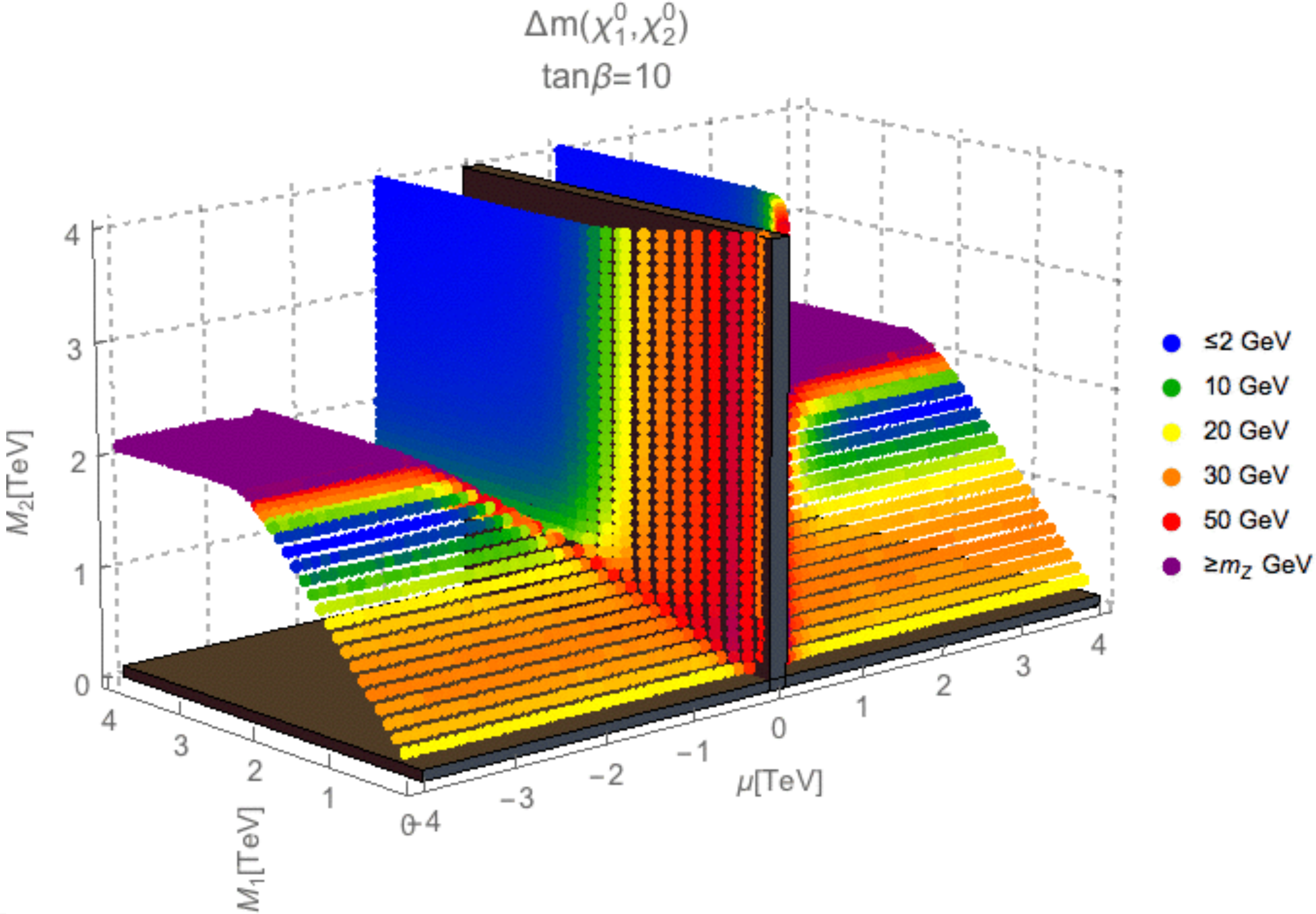
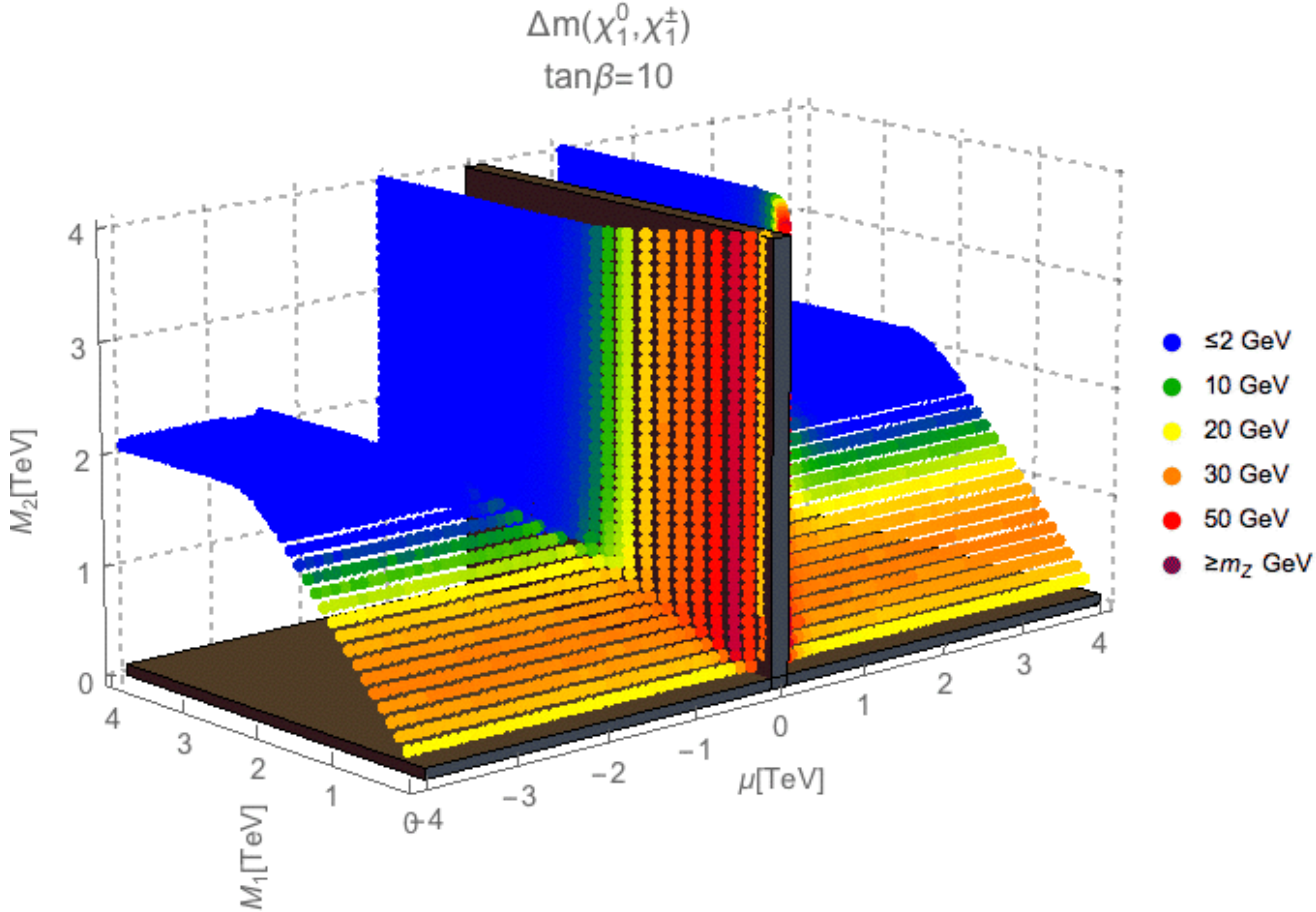


The Well Tempered Surface

Mass difference between the lightest neutralino and chargino



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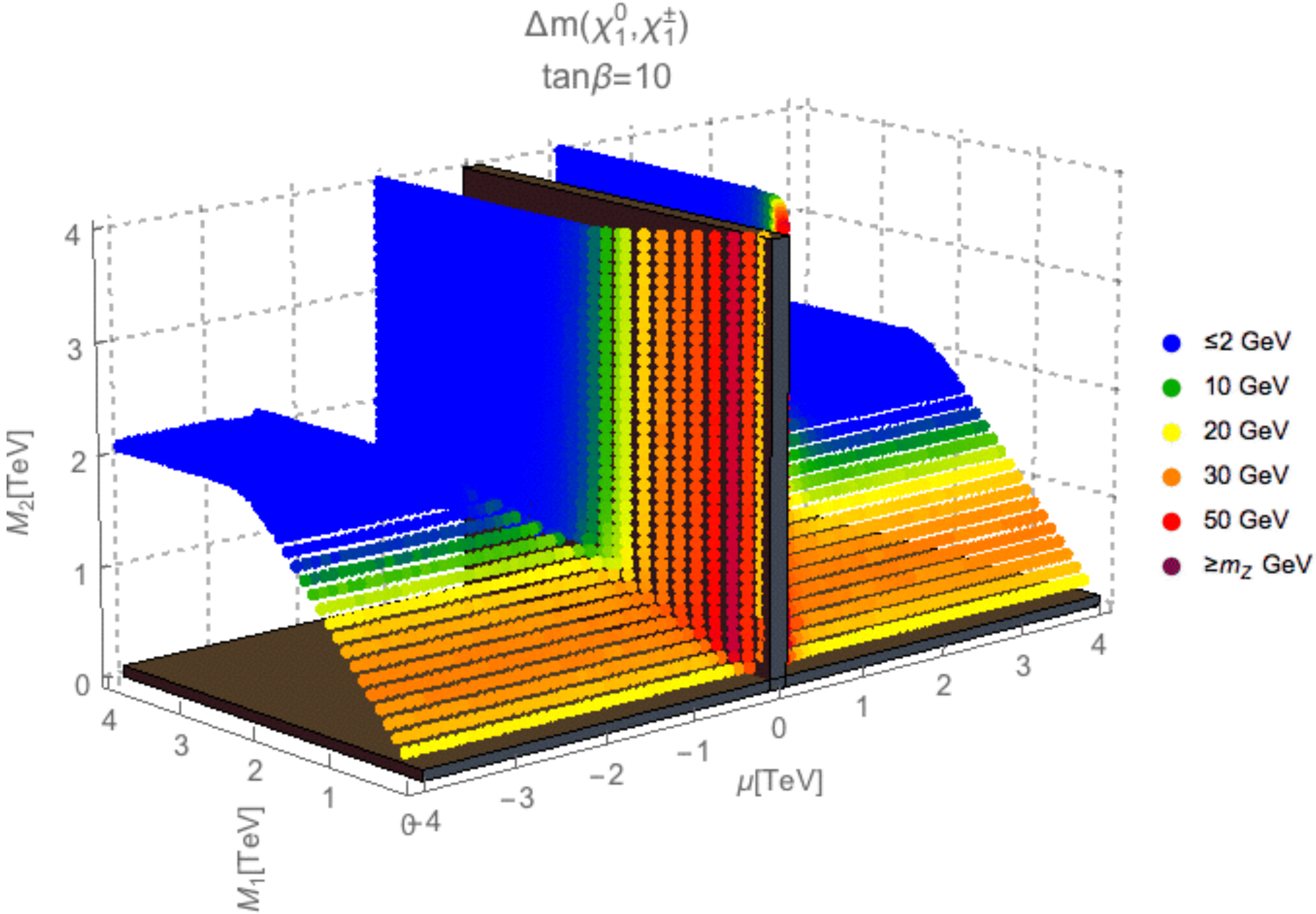

Transition

What have we learned?

- SUSY with R-parity provides a DM candidate
- Not all SUSY DM candidates give correct DM abundance
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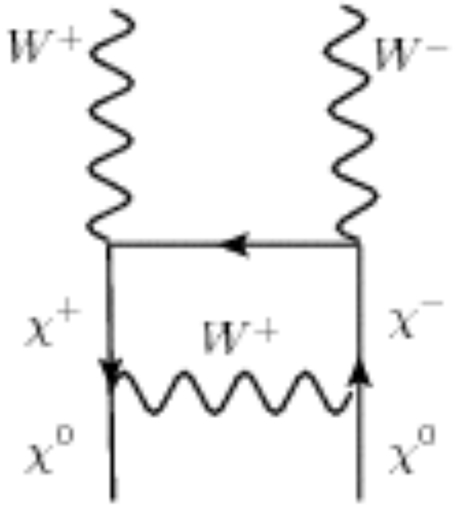
Modifications and improvements

- Sommerfeld enhancement substantially increases pure Wino annihilation cross section
- Some effect for pure Higgsino
- How is the surface affected?
  - Use DarkSE code by Hruczuk

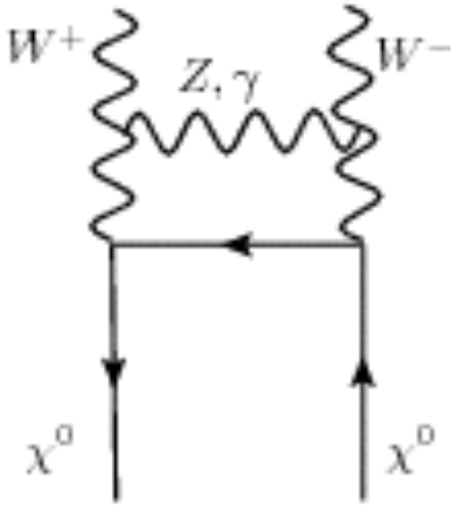
J. Bramante, N. Desai, P. Fox, A. Martin, B. Ostdiek and T. Plehn, “Towards the Final Word on Neutralino Dark Matter,” arXiv:1510.03460 [hep-ph]

What is the Sommerfeld enhancement?

“The modification of the wave function of the incoming non-relativistic particles due to their mutual interaction”



4)



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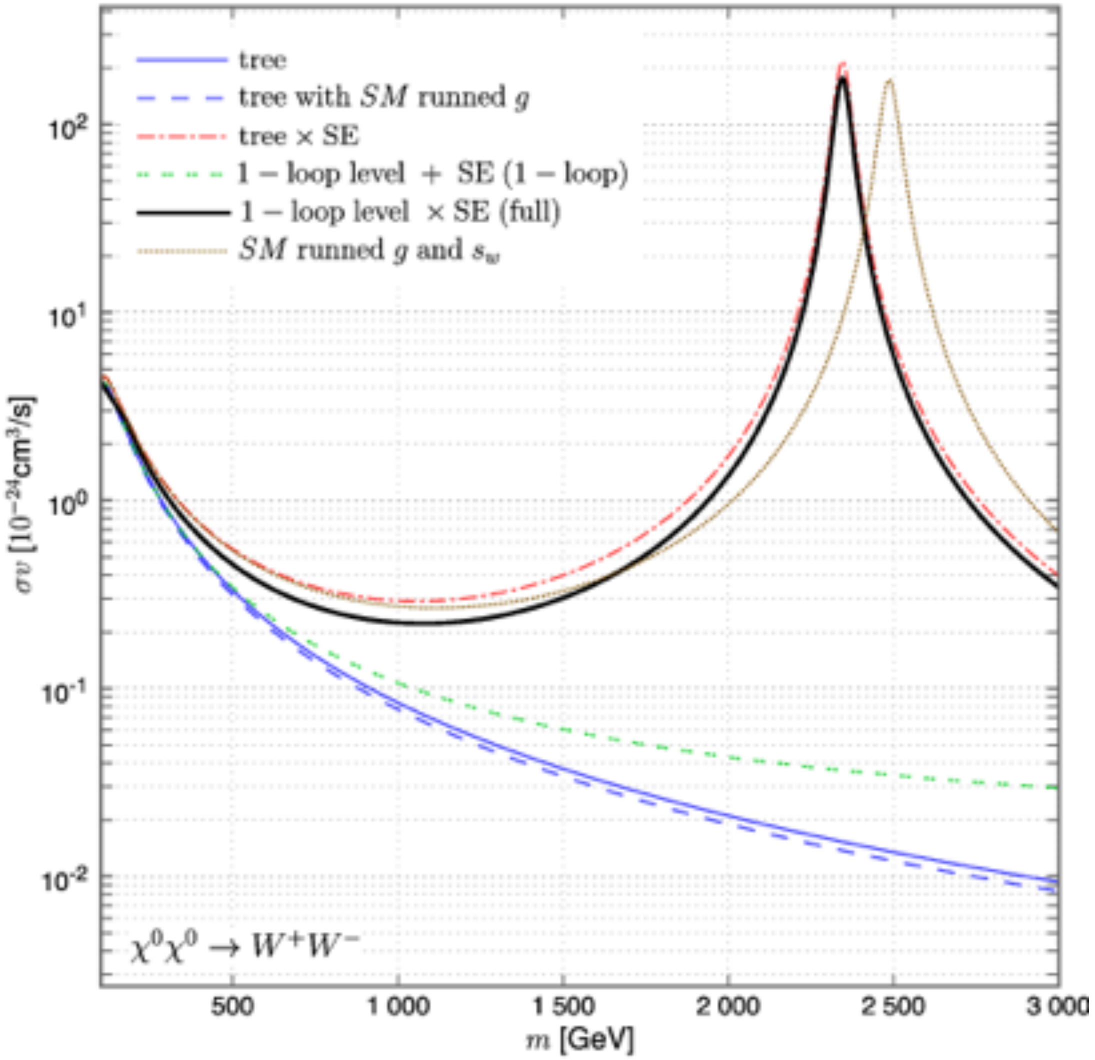
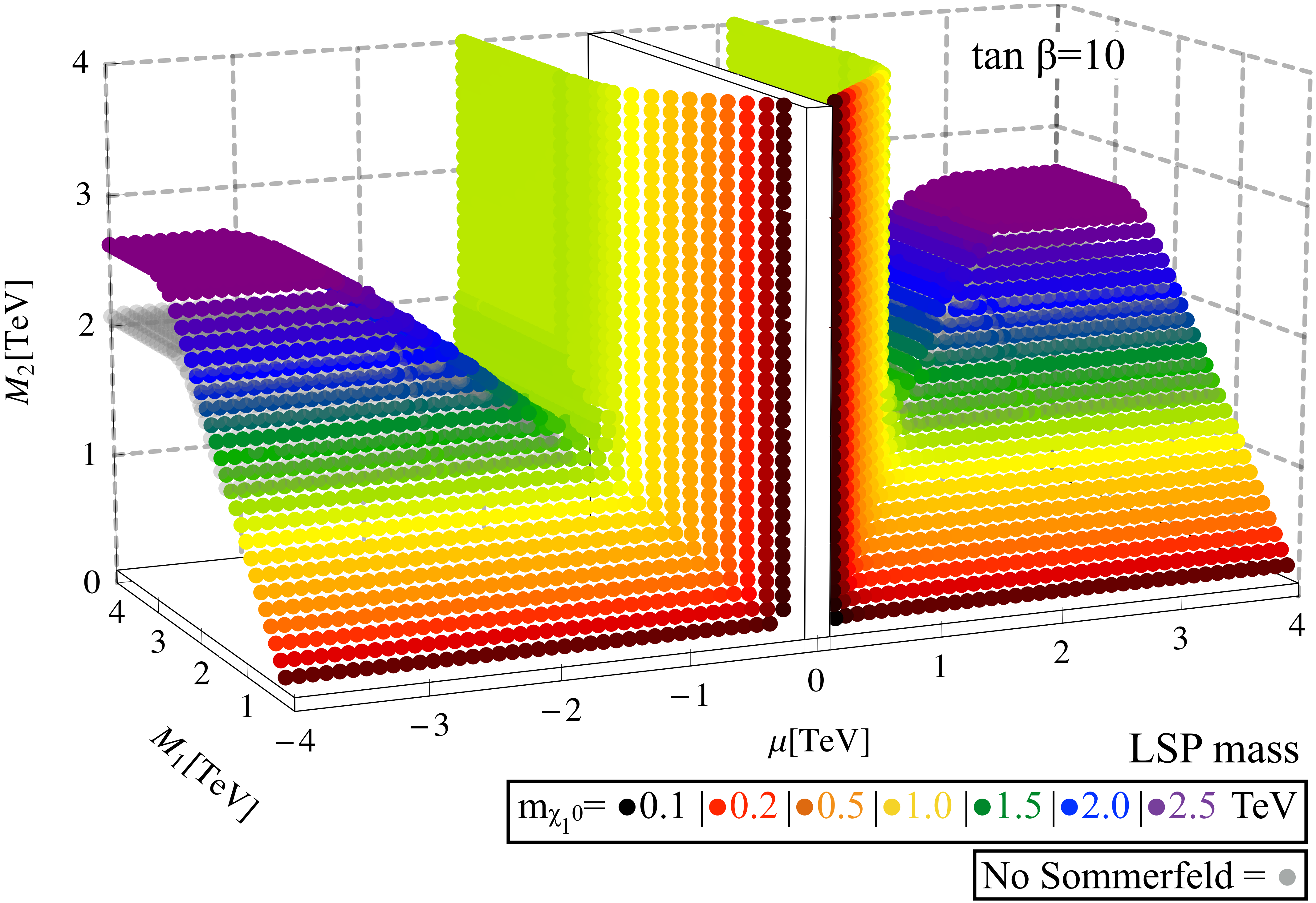


A. Hryczuk and R. Iengo, “The one-loop and Sommerfeld electroweak corrections to the Wino dark matter annihilation,” JHEP **1201**, 163 (2012) [JHEP **1206**, 137 (2012)] dos:10.1007/JHEP01(2012)163, 10.1007/JHEP06(2012)137 [arXiv:1111.2916 [hep-ph]]

Sommerfelded Surface



Where are we going?

Can entire surface be discovered with current/future experiments?

- Examine indirect/direct detection constraints
- Explore search techniques at high energy colliders
- Complementarity between experiments

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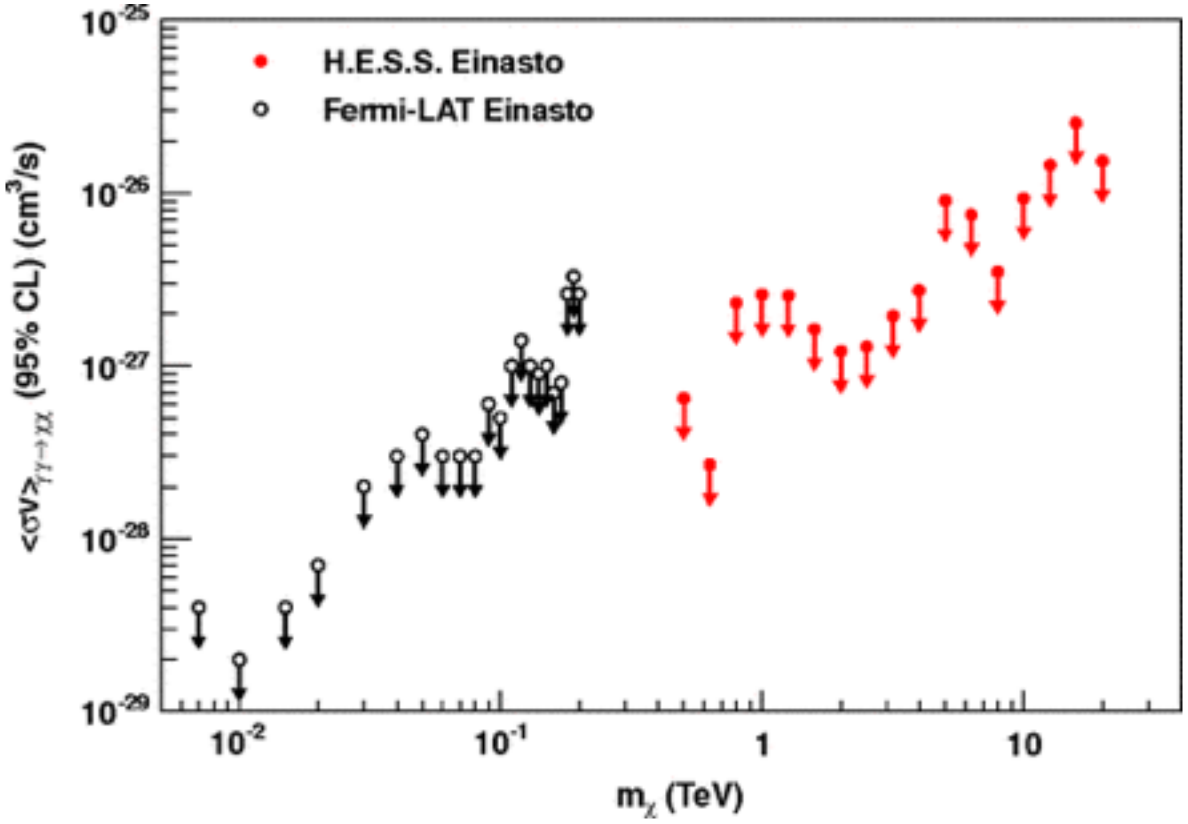
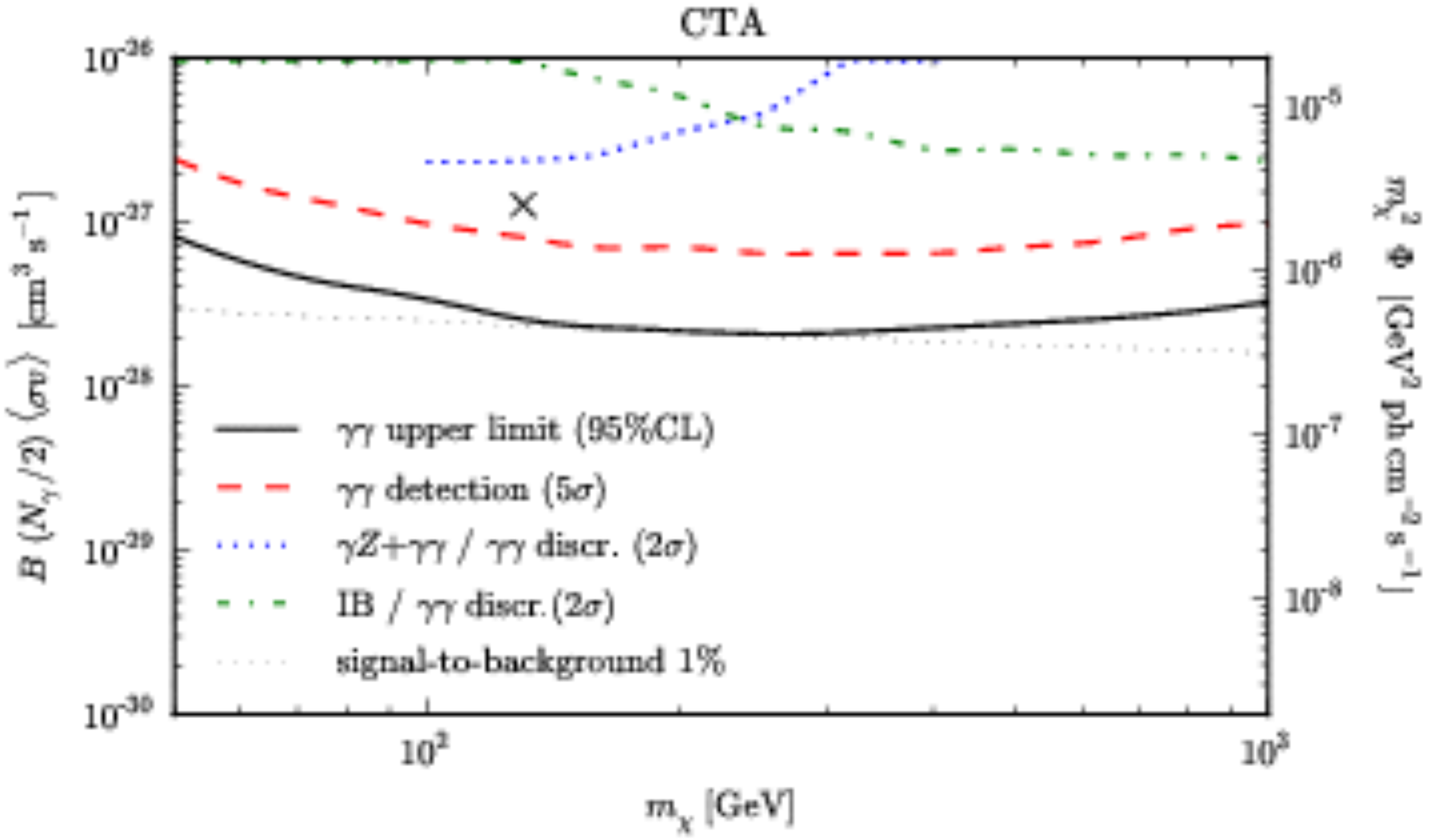
Indirect Detection

- Annihilations still happen in dense regions
- Can do $\chi\chi \to \gamma\gamma$ ($E_\gamma = m_\chi$)
- Lack of signal leads to constraints

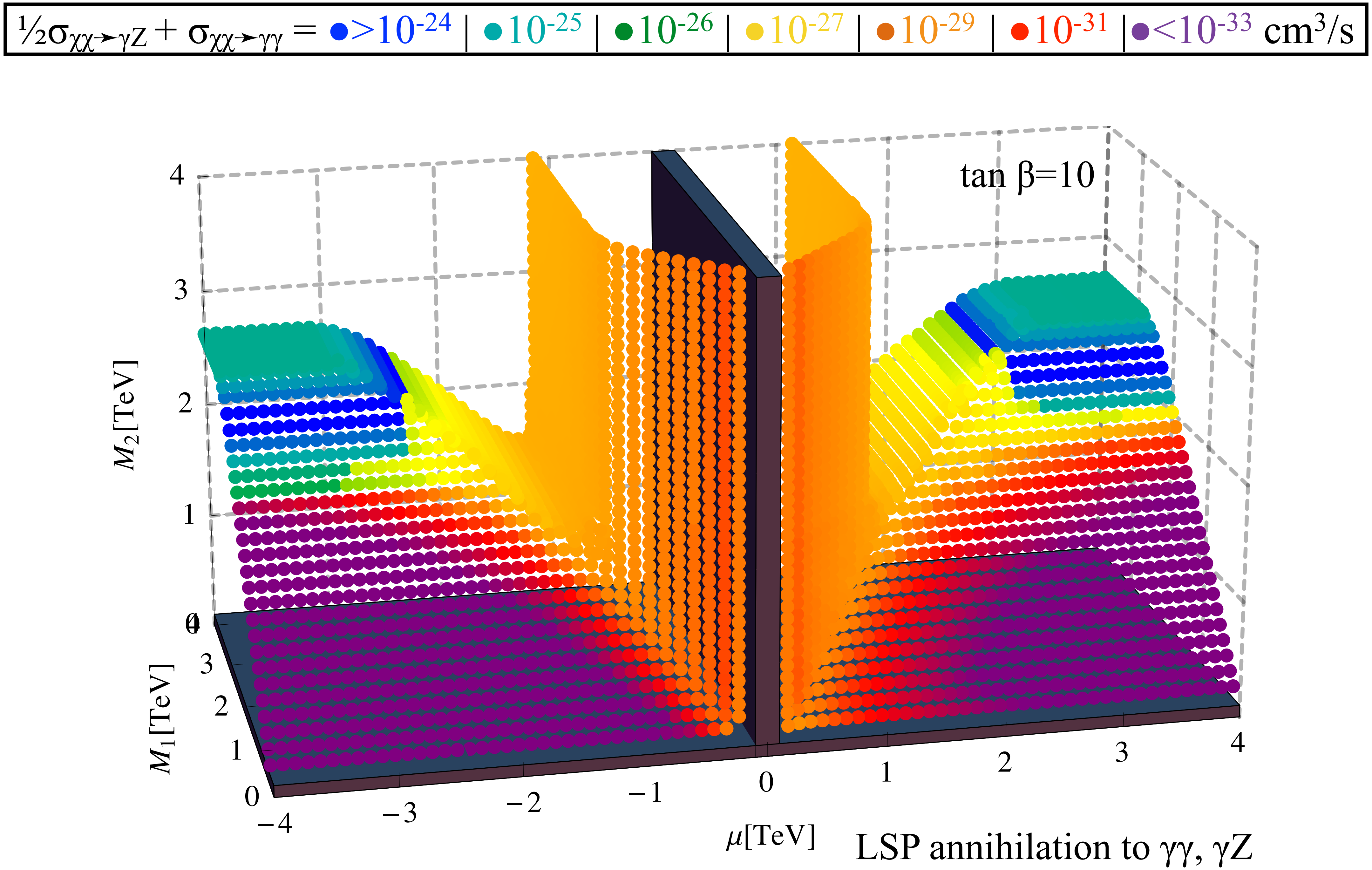


Current



Projection

Indirect Detection



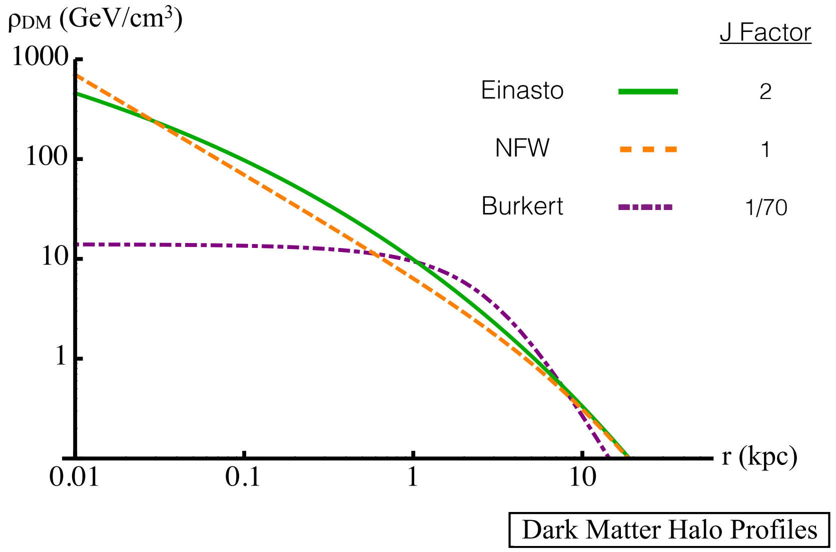
$\frac{1}{2}\sigma_{\chi\chi\to\gamma Z} + \sigma_{\chi\chi\to\gamma\gamma}$ = ● $>10^{-24}$ | ● 10^{-25} | ● 10^{-26} | ● 10^{-27} | ● 10^{-29} | ● 10^{-31} | ● $<10^{-33}$ cm^3/s

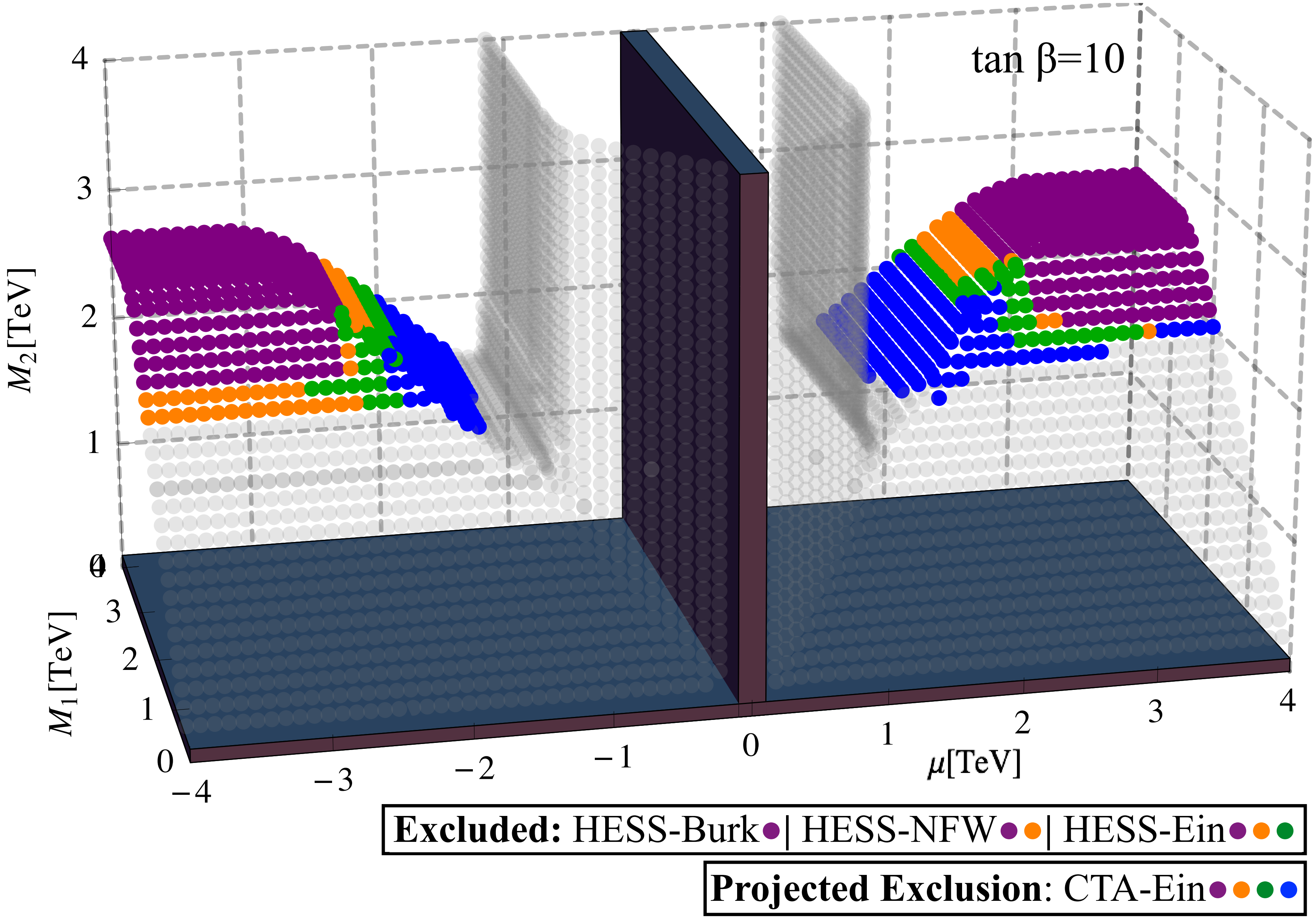
LSP annihilation to γγ, γZ

Sommerfeld effect enhances annihilation to photons

Indirect Detection

- Constraint depends on DM profile





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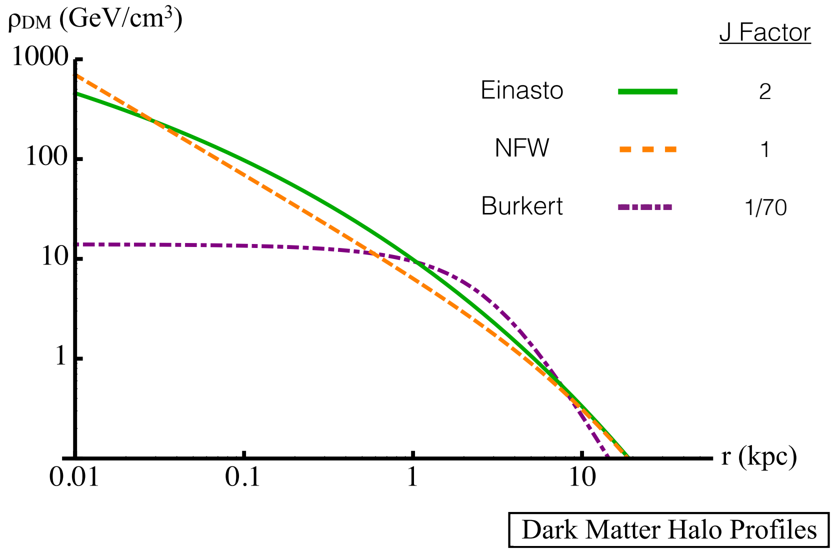
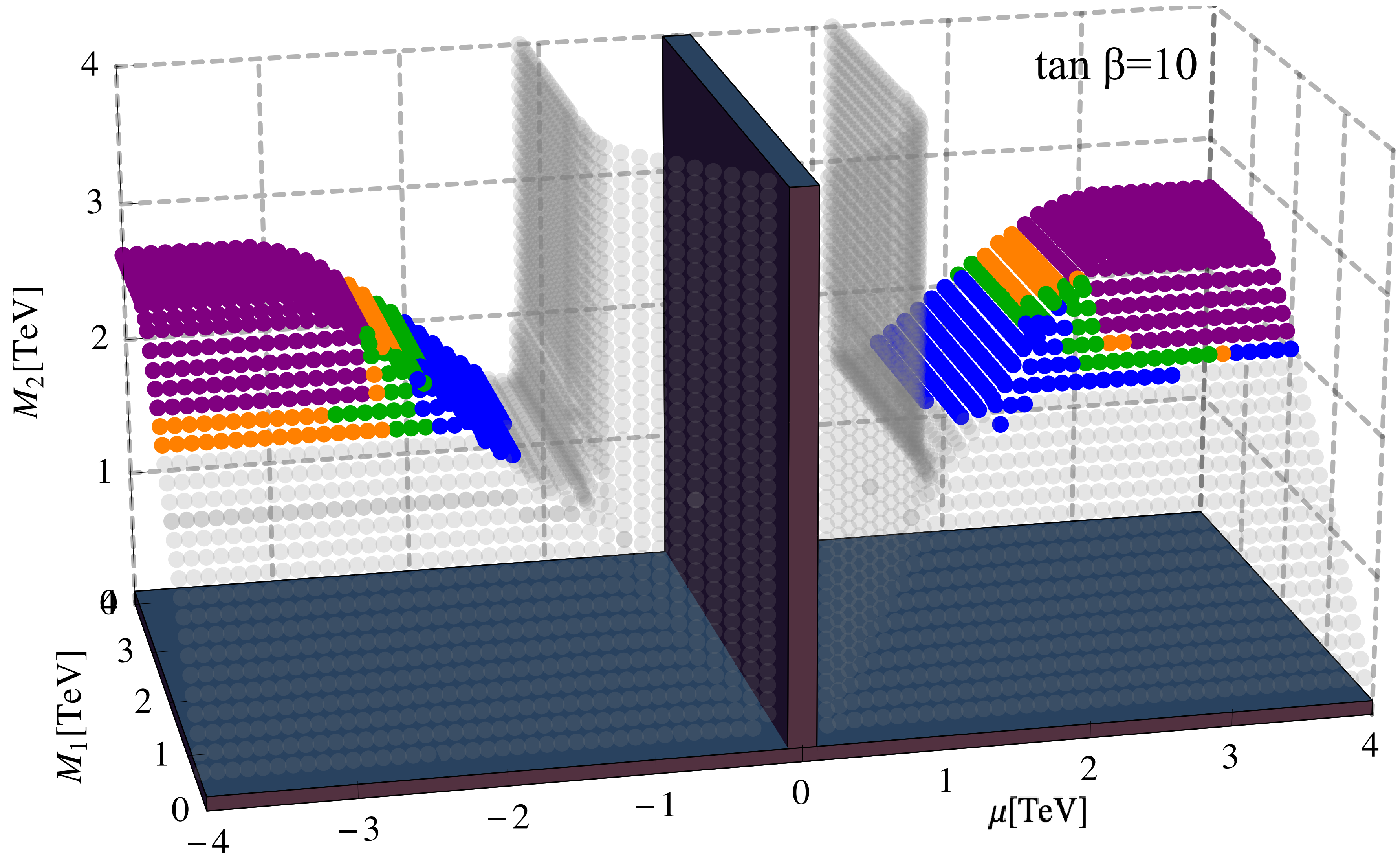


Dark Matter Halo Profiles



Excluded: HESS-Burk● | HESS-NFW●● | HESS-Ein●●●

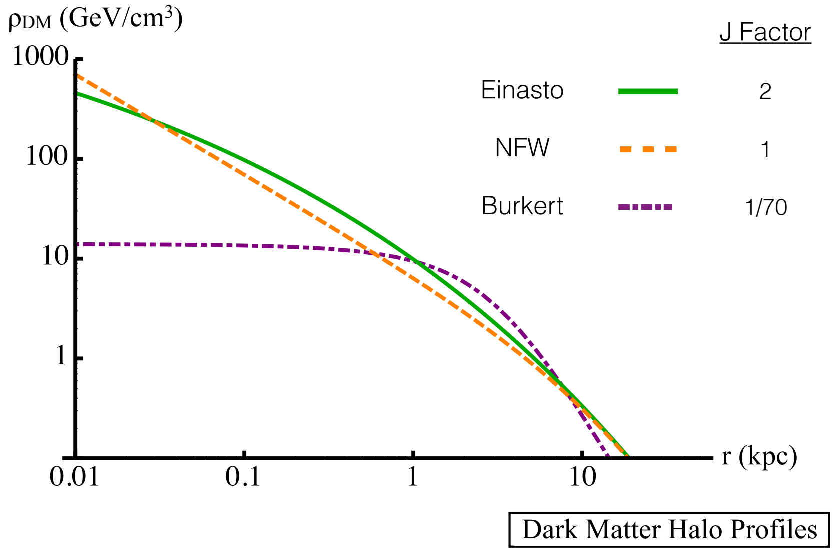
Projected Exclusion: CTA-Ein●●●●

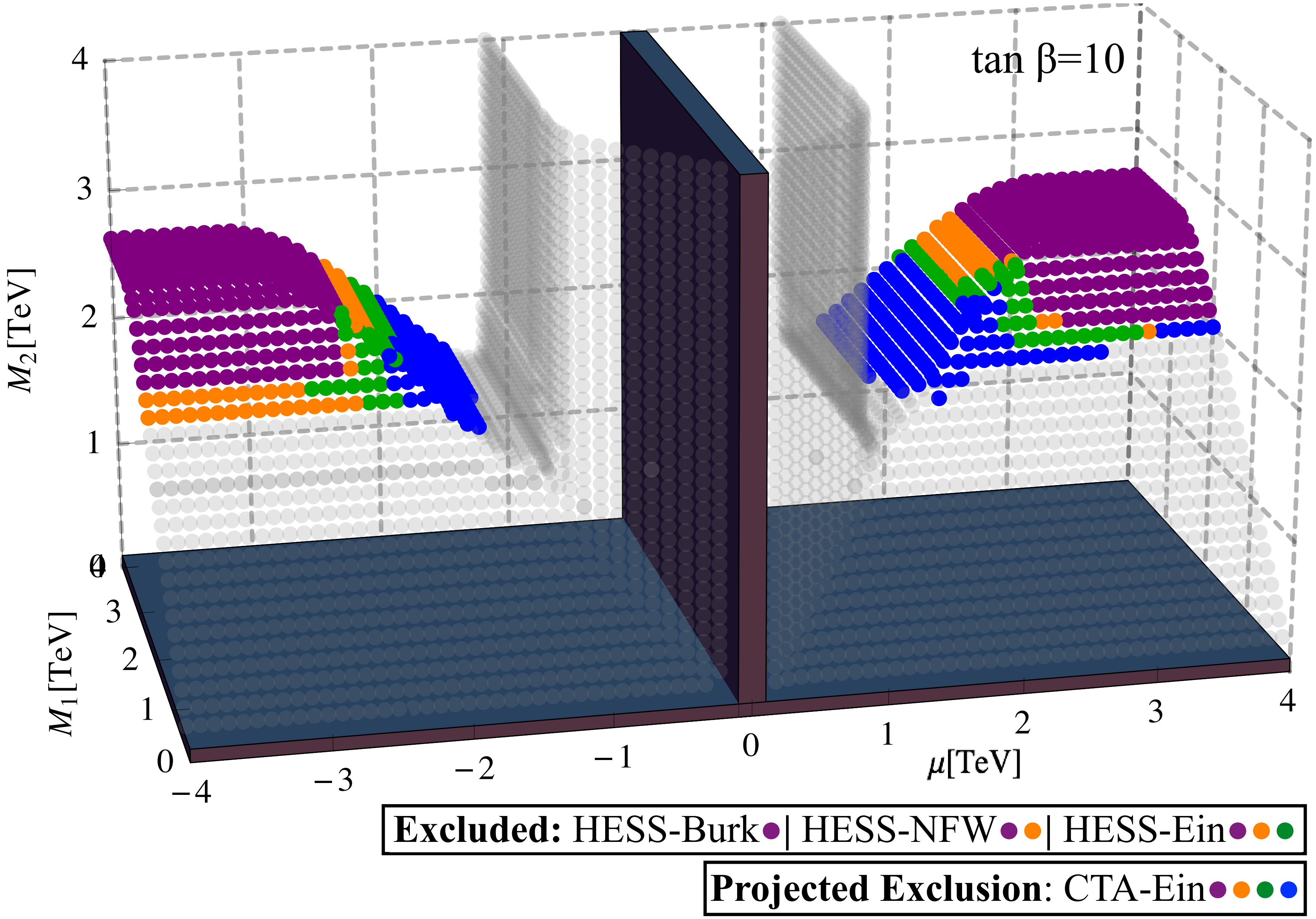
★ Pure Wino plane excluded

- Wino-Higgsino sheet in future

Indirect Detection

- Constraint depends on DM profile





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Direct Detection

- Look for DM scattering off nucleon in detector material

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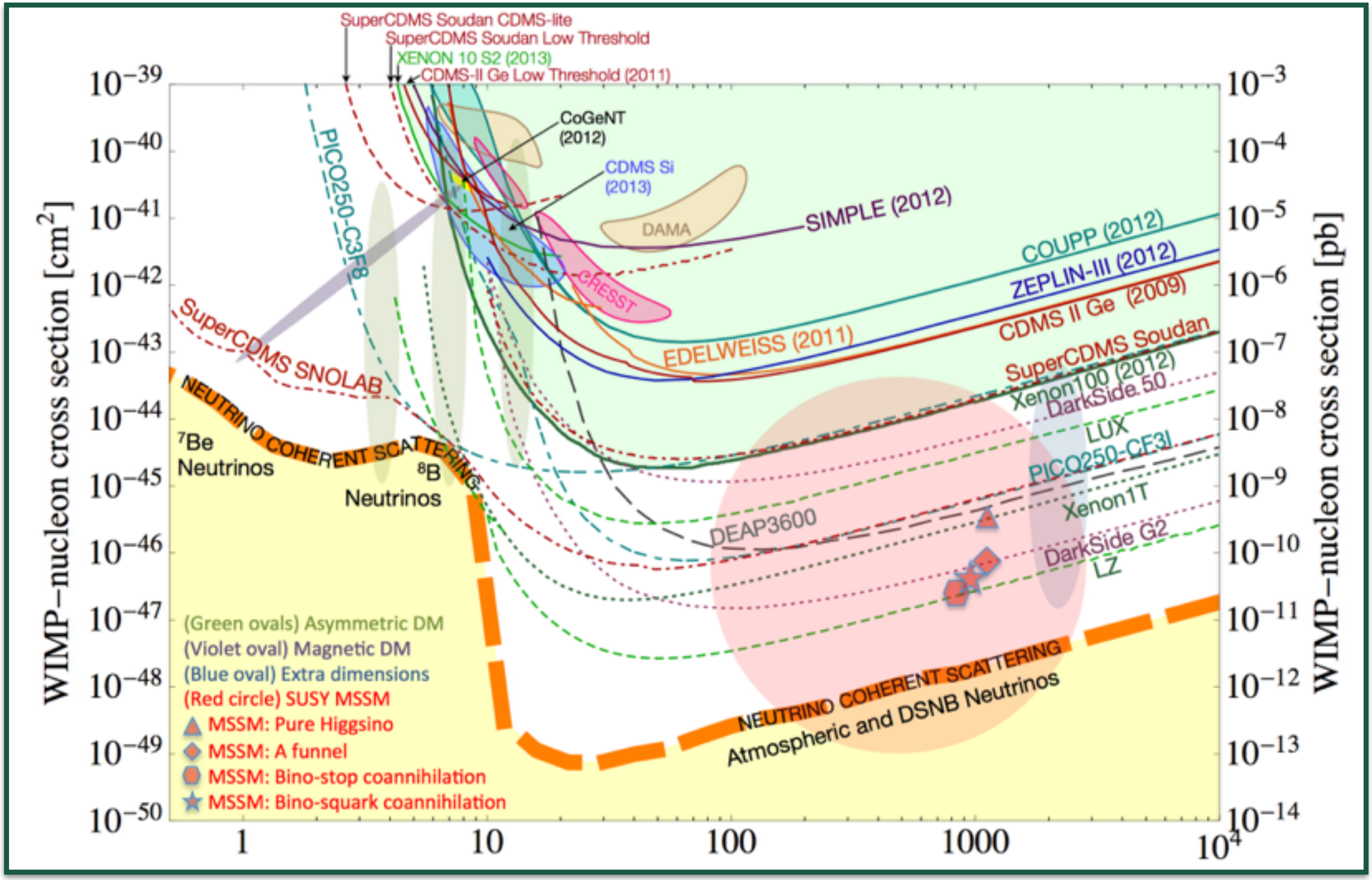

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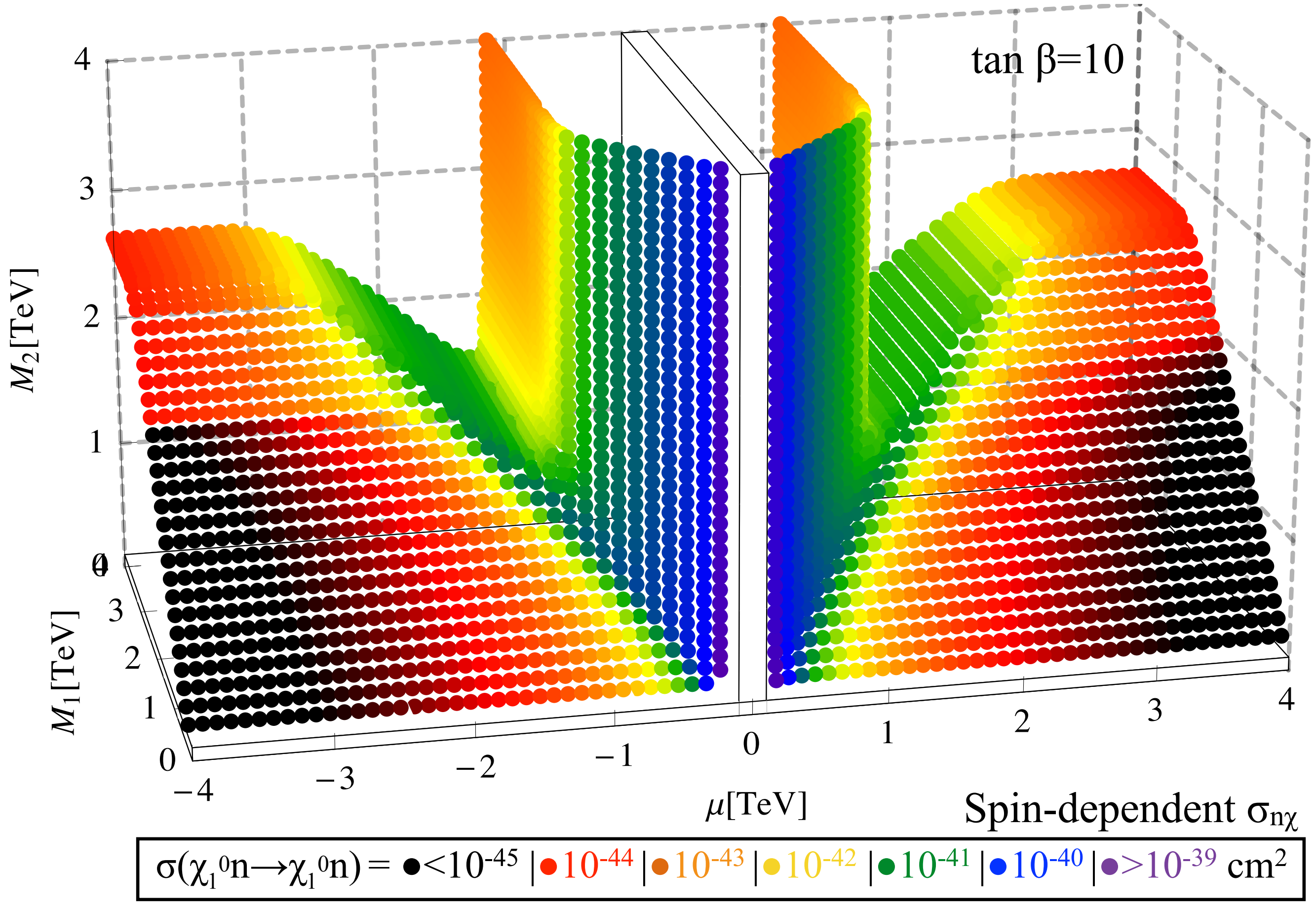
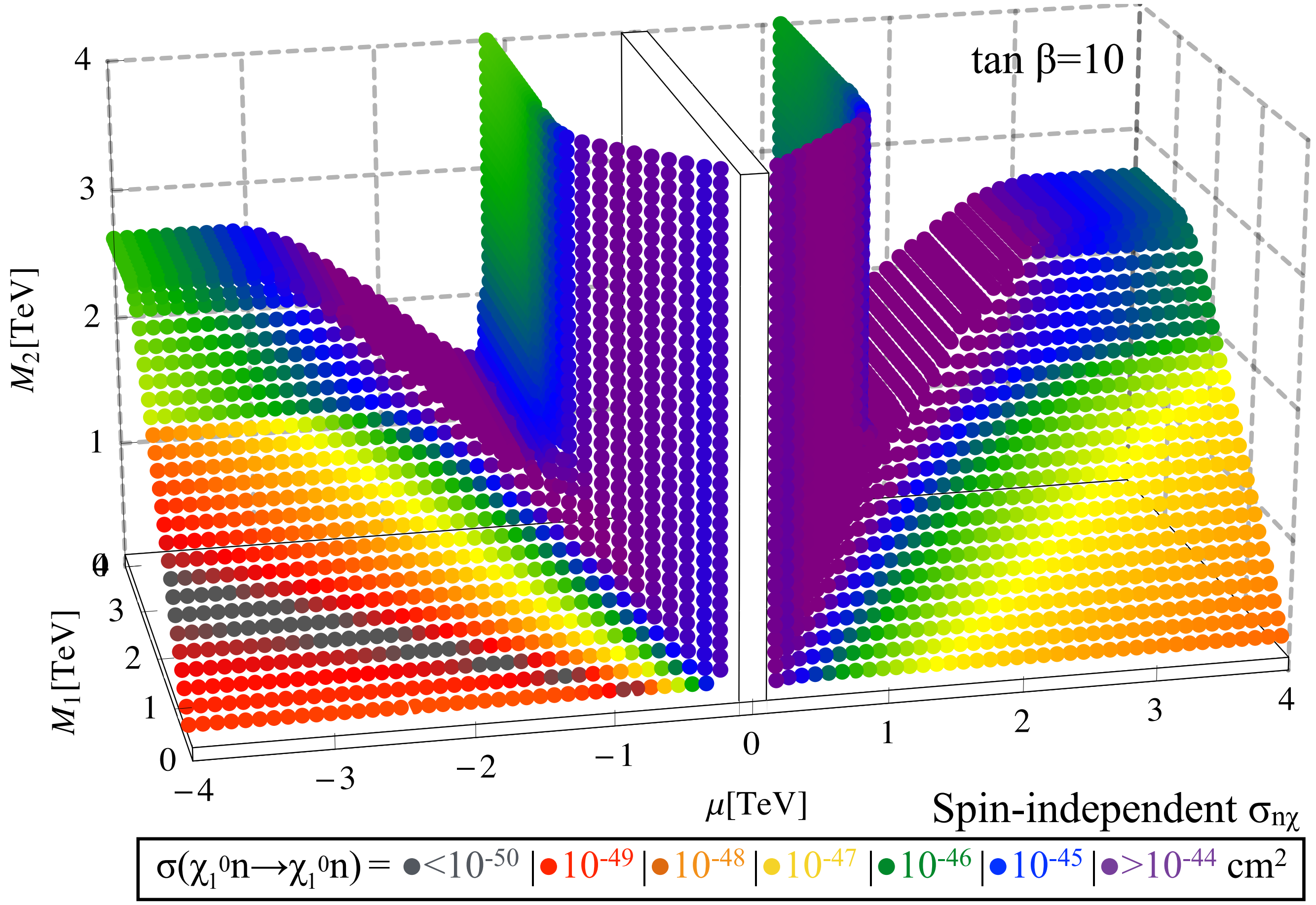




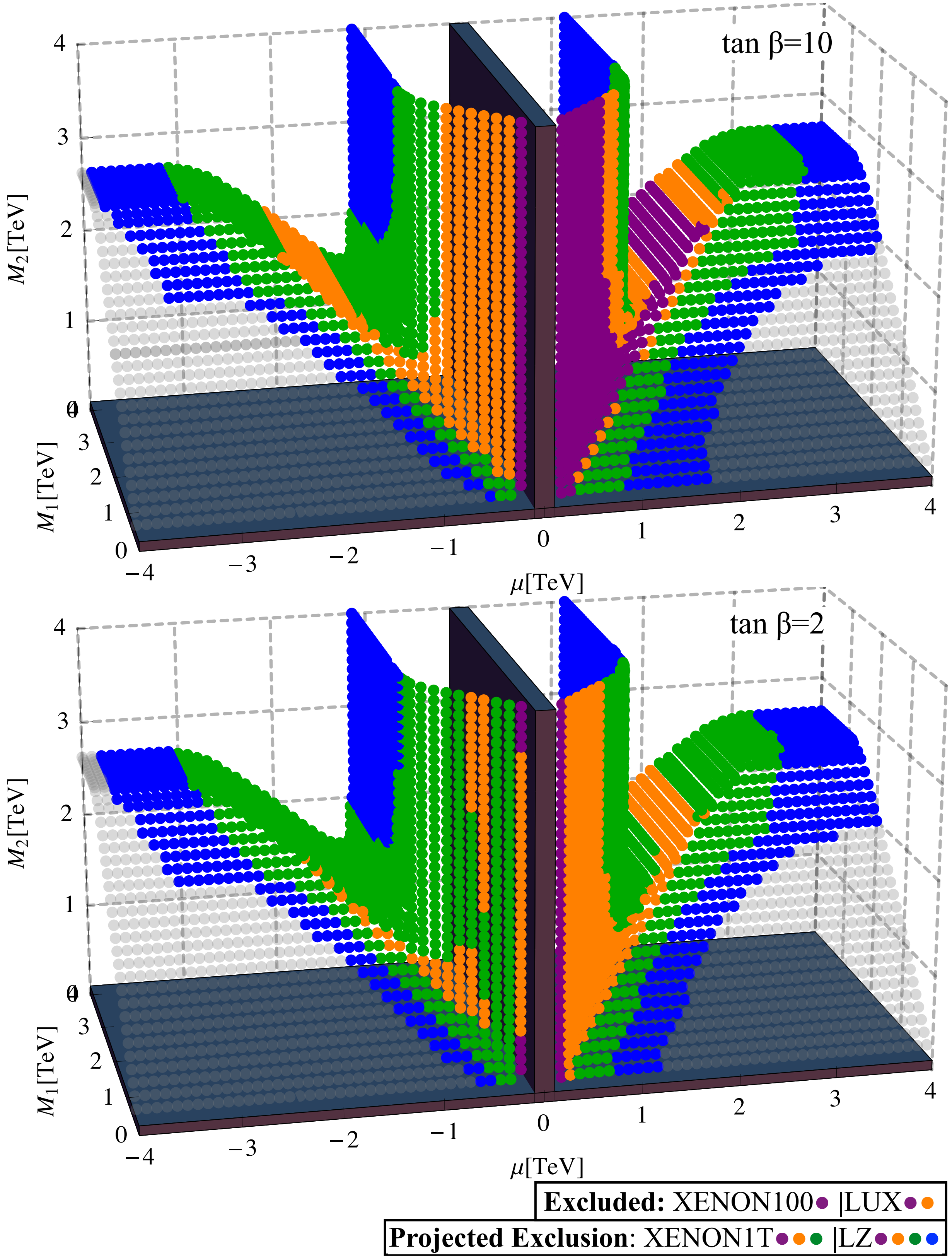
$\sigma \propto$ Coupling to Z

$\sigma \propto$ Coupling to h

Accidental cancelations in coupling of LSP to Z(h) leads to blind spots

Direct Detection

- Spin-independent bounds are much better
- Exclusions depend on tan β



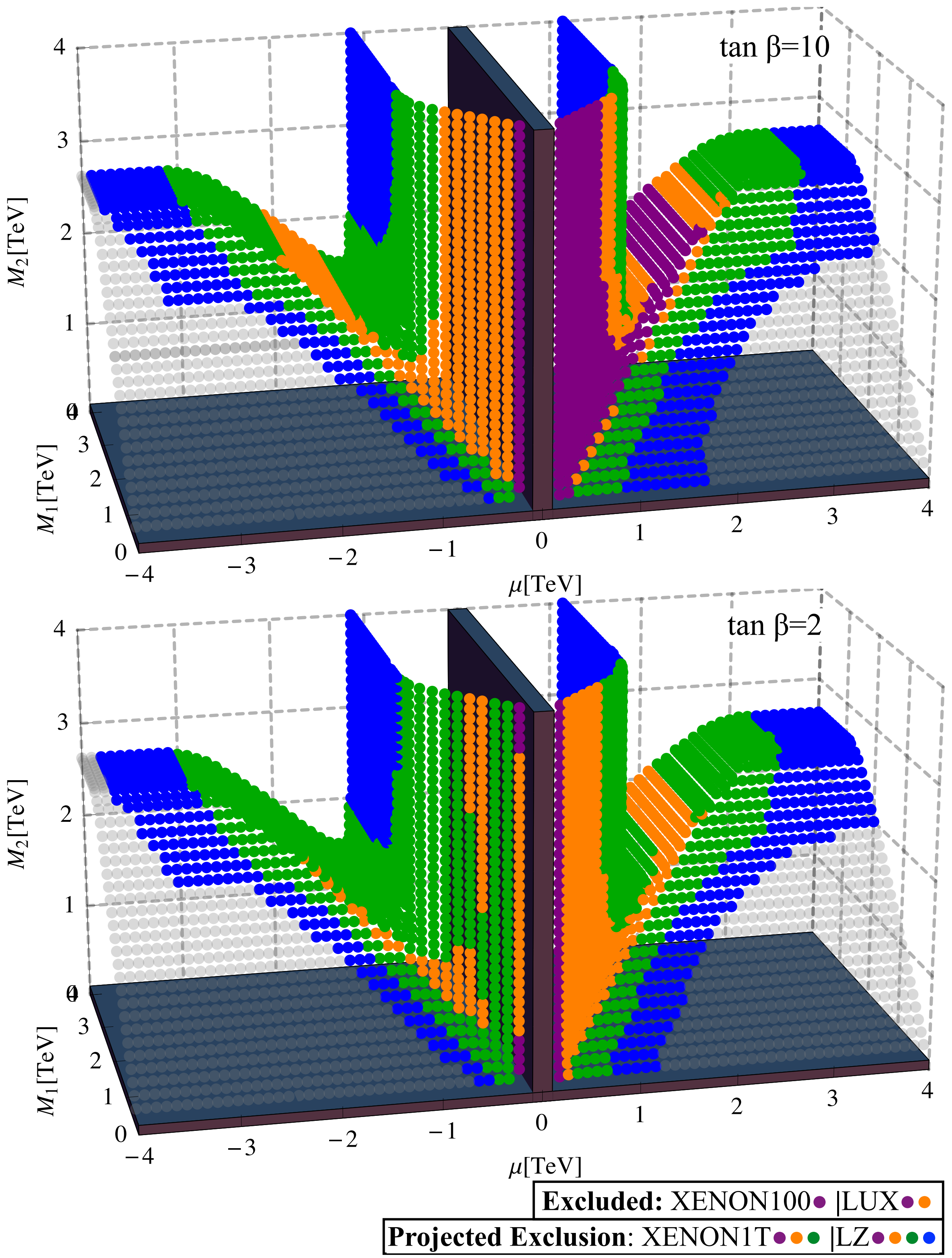
Direct Detection

- Spin-independent bounds are much better
- Exclusions depend on tan β

★ Bino-Higgsino and Wino-Higgsino are or will be excluded

★ M_1, $M_2 \leq 4000$ GeV not decoupled enough… \`Pure' Higgsino discoverable in future

★ Pure Wino mostly covered



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<u>Can entire surface be discovered with current/future experiments?</u>

- Examine Direct/Indirect Detection constraints

★ Pure Wino and Wino-Higgsino covered by indirect detection
★ Bino-Higgsino , Wino-Higgsino, `Pure Higgsino', and some Wino surface covered by direct detection
✳ No coverage for Bino-Wino
✳ Depend on *astrophysical assumptions*

- Explore search techniques at high energy colliders
- Complementarity between experiments

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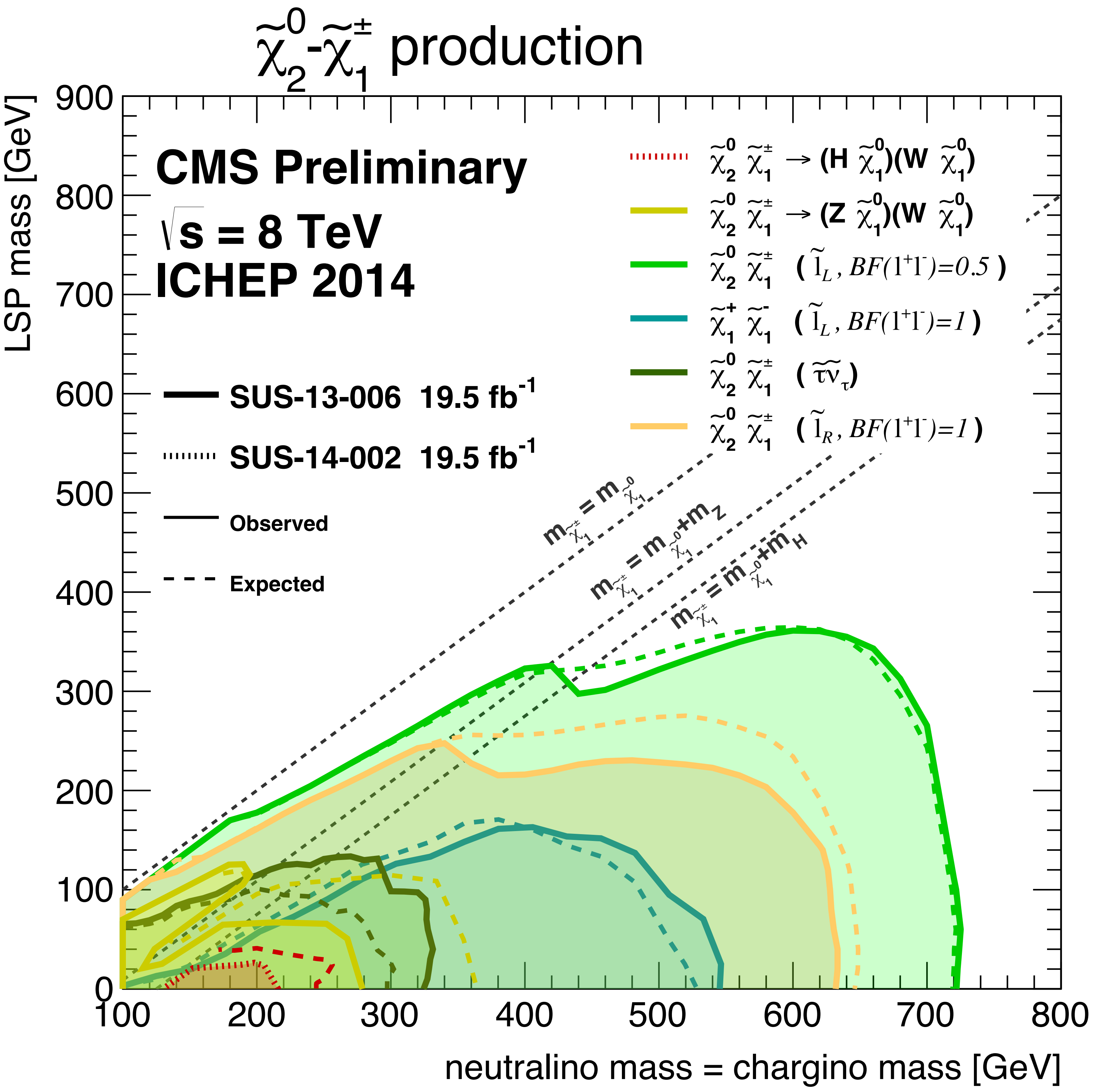
❒ Cover Bino-Wino surface
❒ Resolve conflicts with pure wino

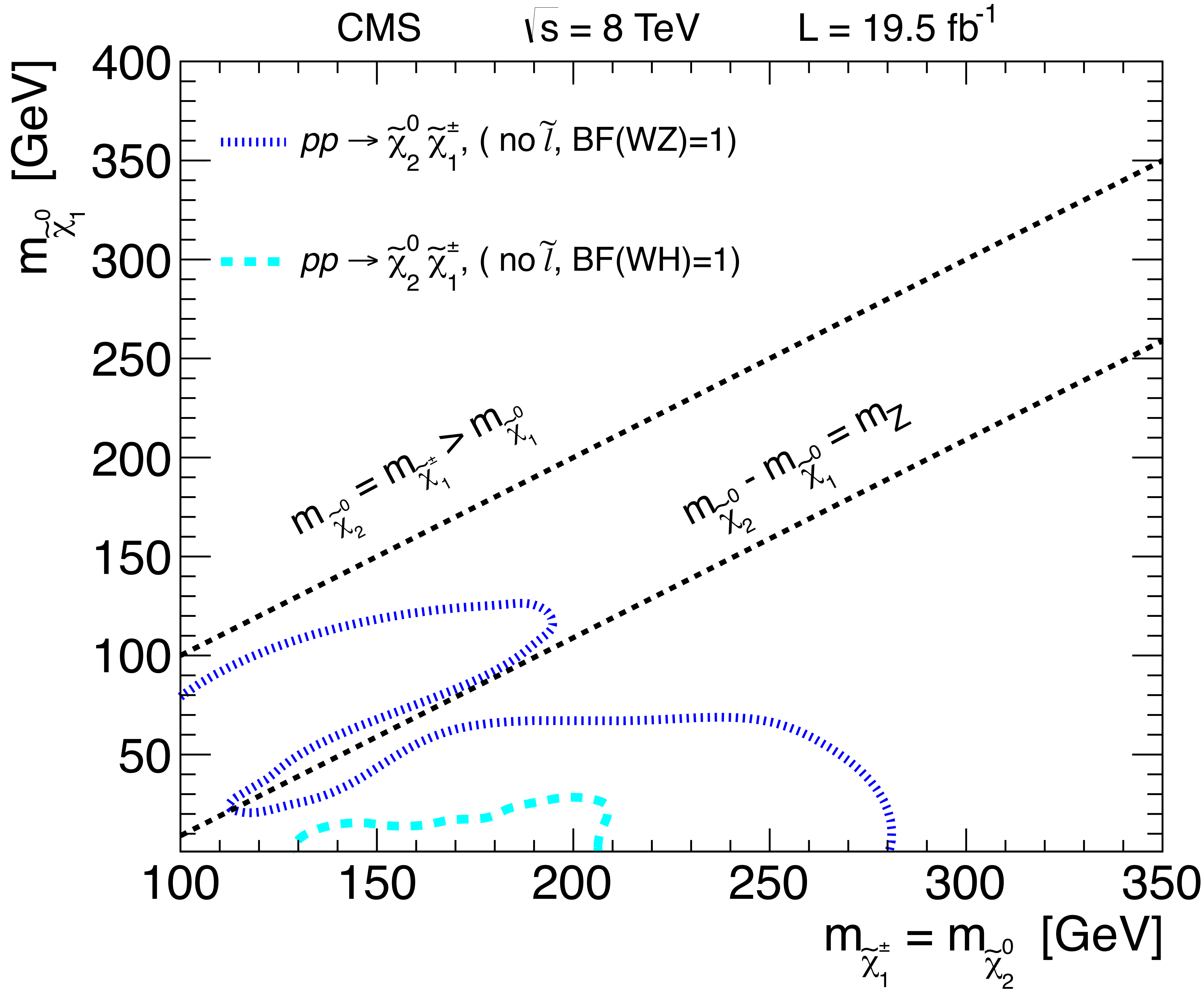
LHC Detectors can distinguish
- Leptons (electrons and muons)
- Photons
- Anything with quarks seen as ‘jet’
- Neutrinos and dark matter not detected; conservation of transverse momentum

- Complementarity between experiments

What limits exist already?



What limits exist already?



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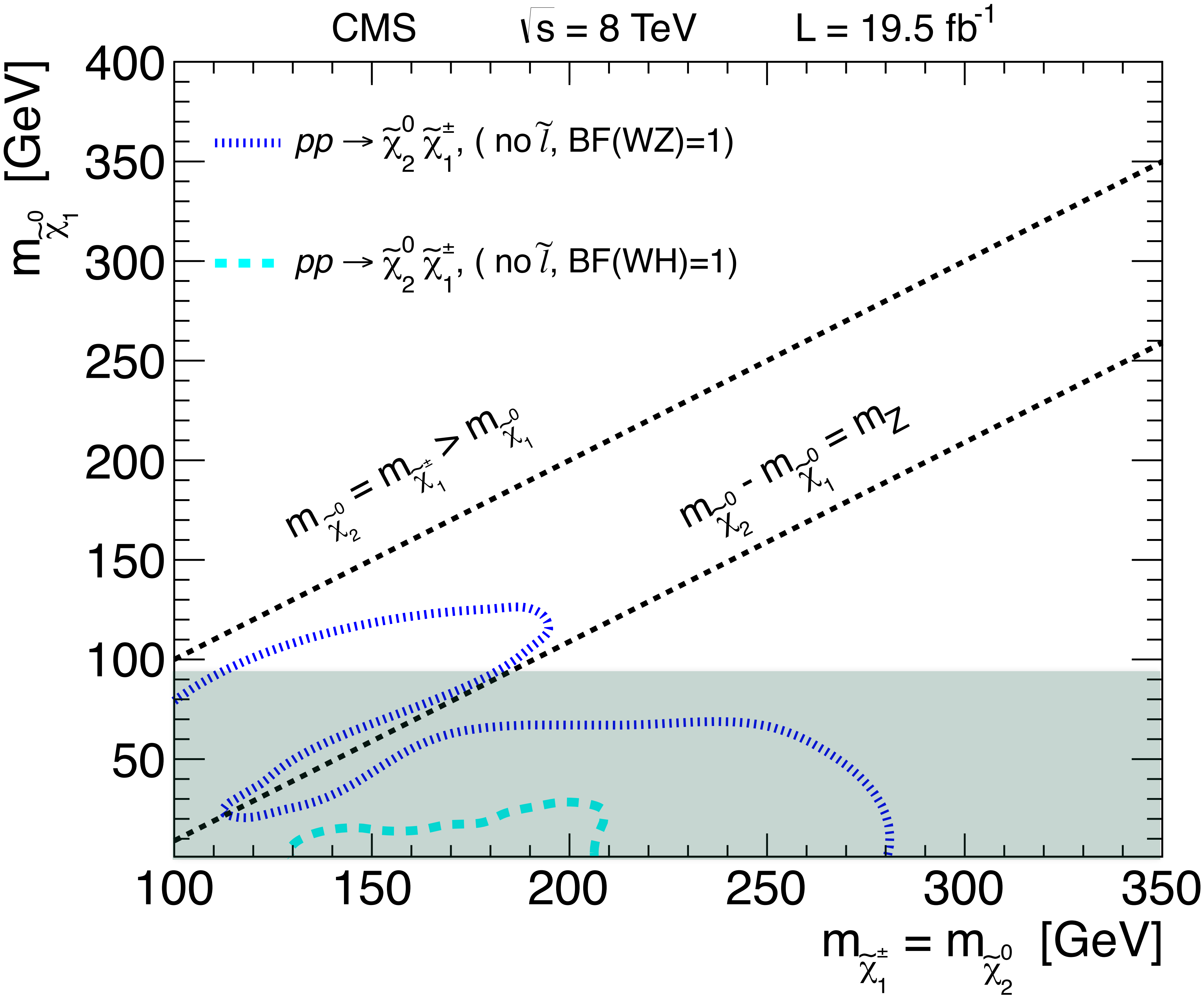
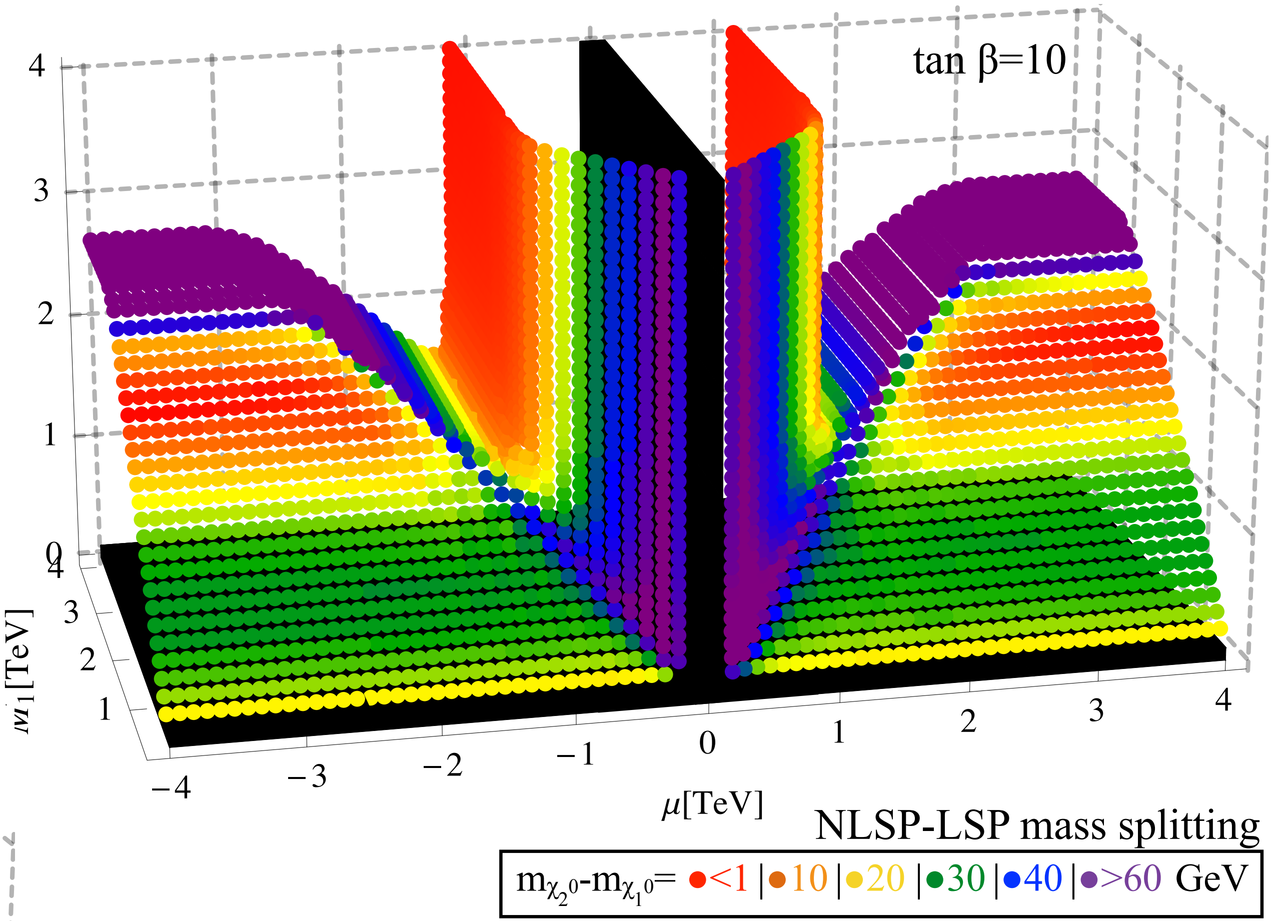
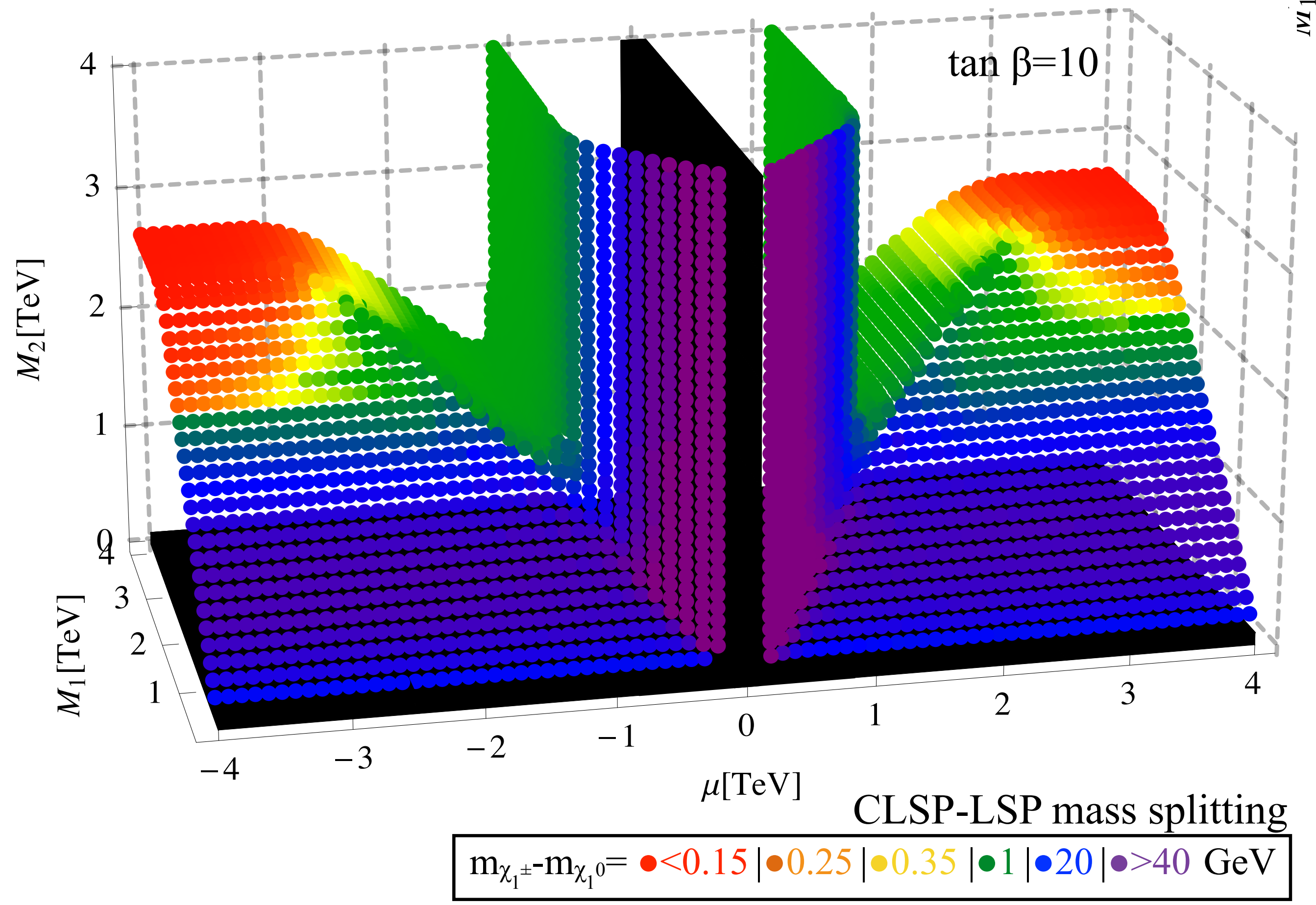


LEP: m_{χ^+}>94 GeV

What limits exist already?

Reminder of mass splittings





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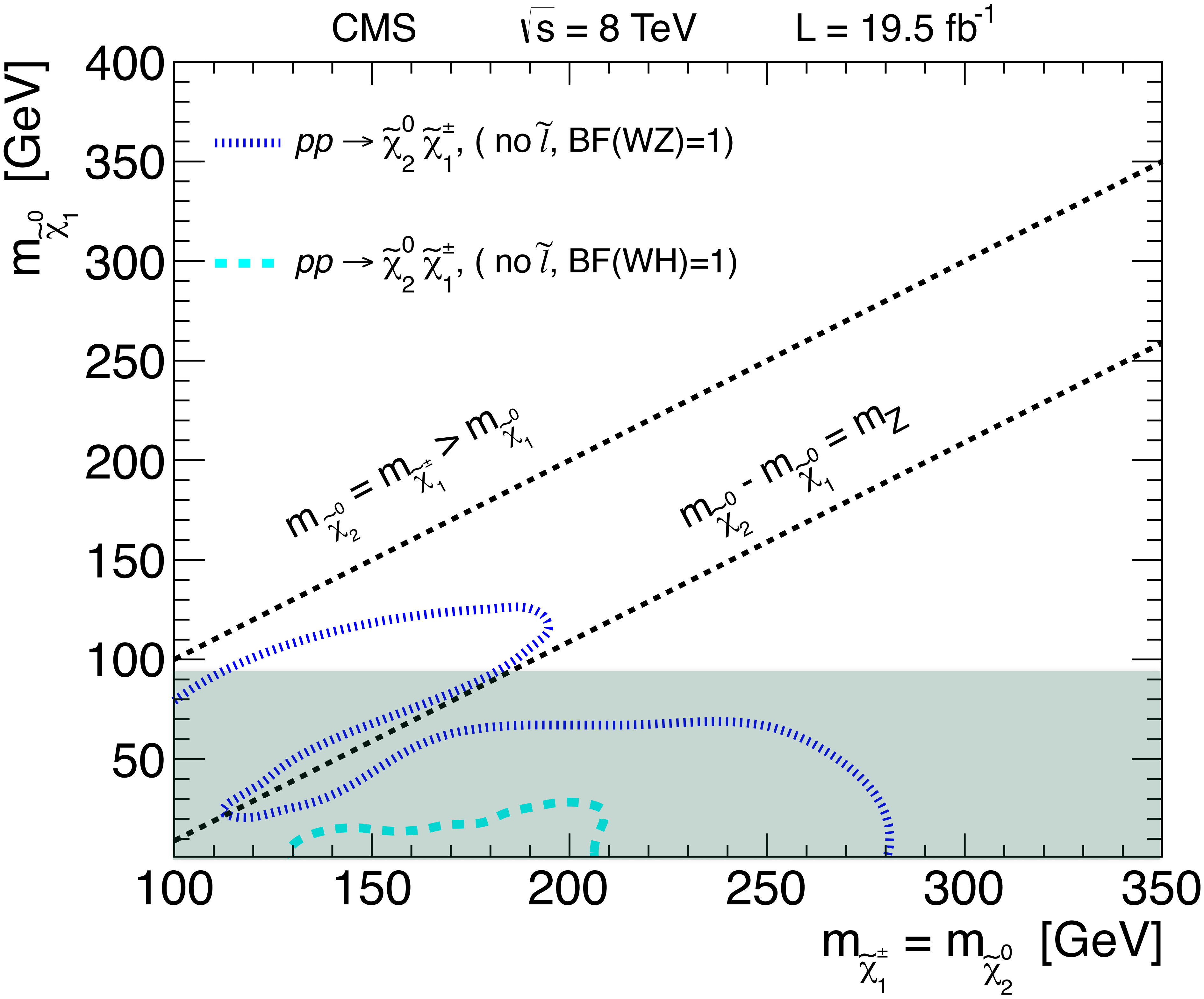
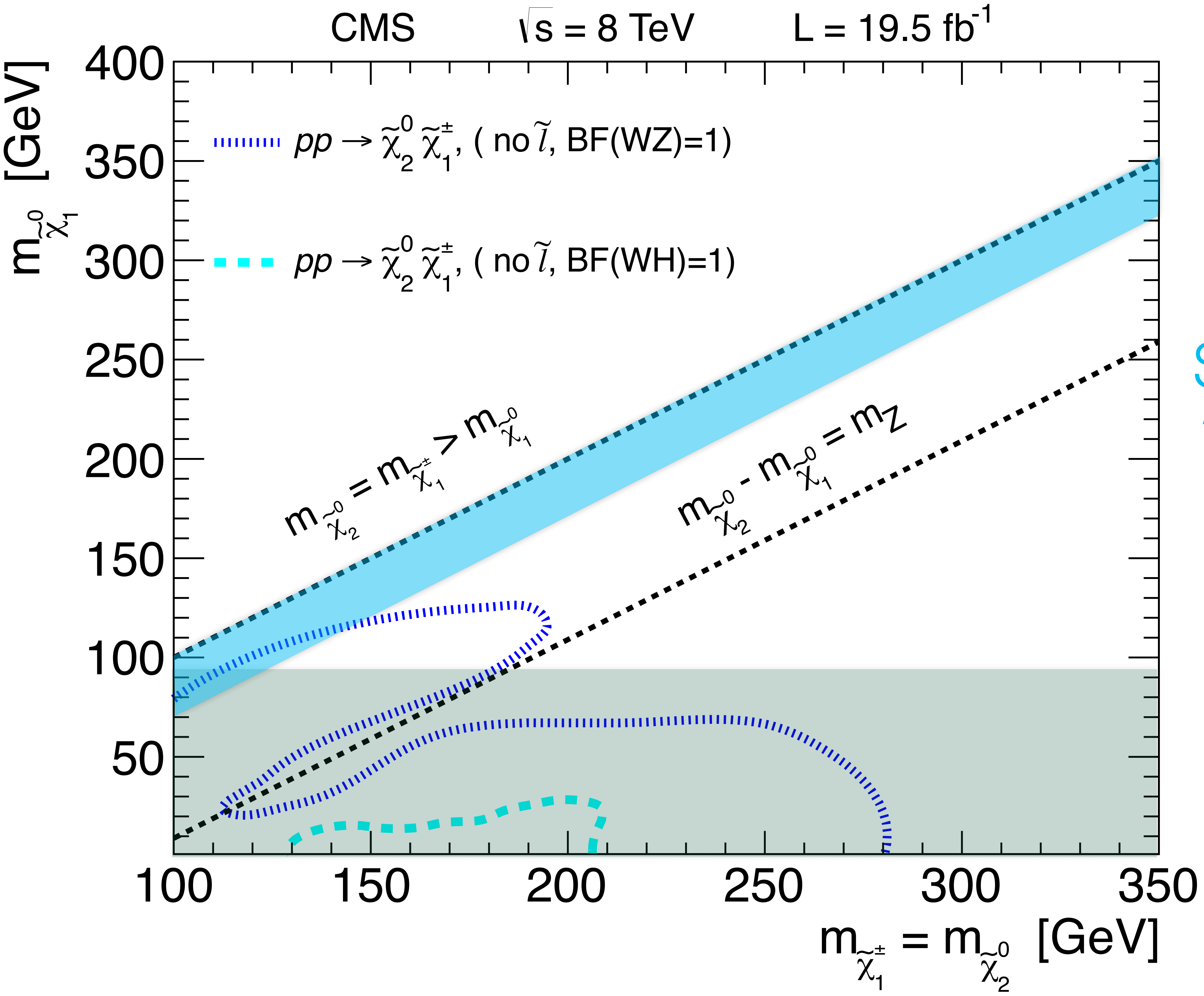


LEP: $m_{\chi+}$>94 GeV

What limits exist already?



LEP: m_{χ^+}>94 GeV

Surface:

$$m_{\chi^+}, m_{\chi_2^0} \lesssim m_{\chi_1^0} + 30$$

Need new methods

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- Few SUSY searches so far use photons
- Can light be used to search for dark matter?

$$pp \to \gamma + \ell^+\ell^- + \not{E}_T$$

Neutral current aimed at production of $\chi_2^0\chi_3^0$

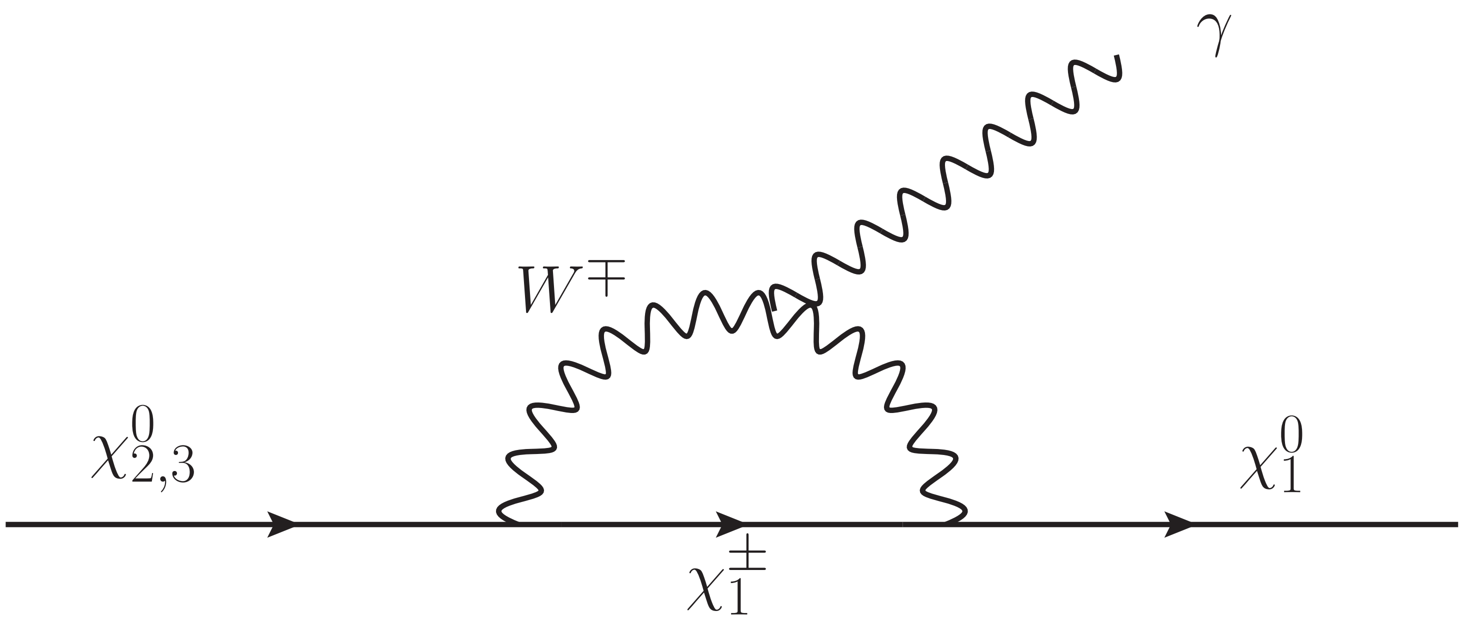
- J. Bramante, A. Delgado, F. Elahi, A. Martin and BO, "Catching sparks from well-forged neutralinos," Phys. Rev. D 90, no. 9, 095008 (2014) [arXiv:1408.6530 [hep-ph]]

$$pp \to \gamma + \ell^\pm + \not{E}_T$$

Charged current aimed at production of $\chi_2^0\chi_1^+$

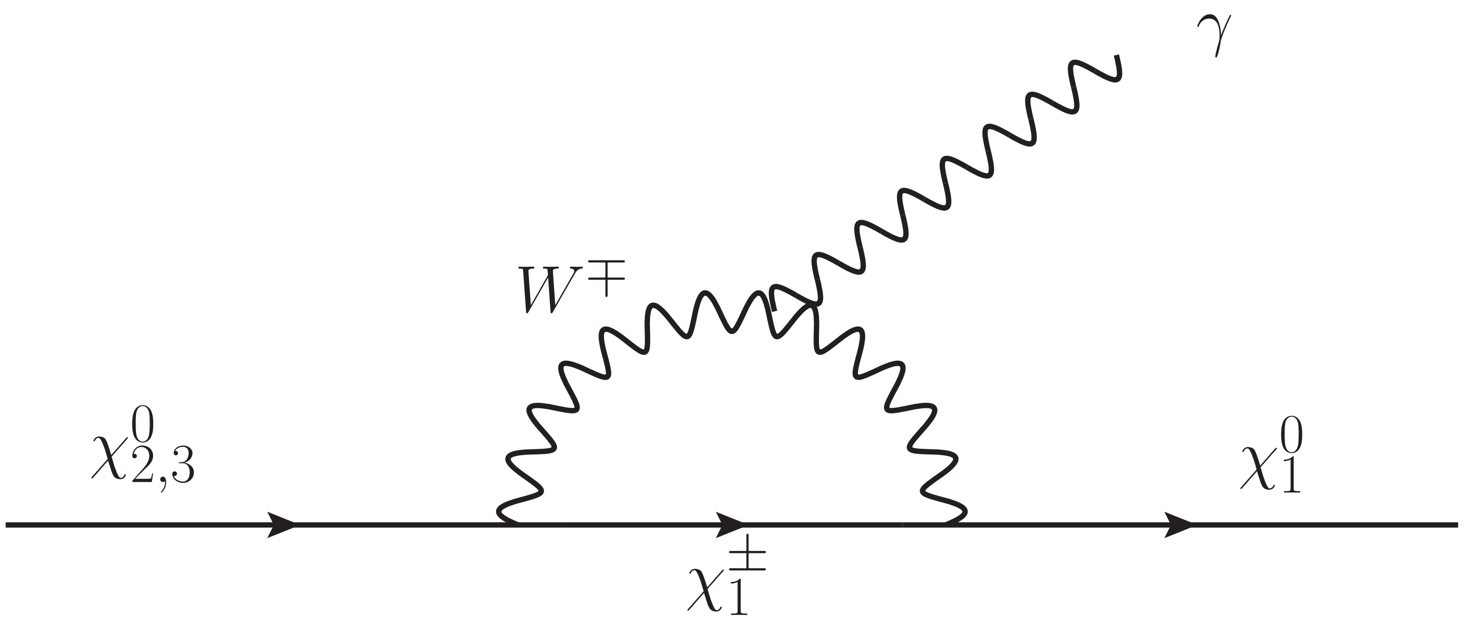
- J. Bramante, P. J. Fox, A. Martin, BO, T. Plehn, T. Schell and M. Takeuchi, "Relic neutralino surface at a 100 TeV collider," Phys. Rev. D 91, no. 5, 054015 (2015) [arXiv:1412.4789 [hep-ph]]
- J. Bramante, N. Desai, P. Fox, A. Martin, BO, and T. Plehn, "Towards the Final Word on Neutralino Dark Matter," arXiv:1510.03460 [hep-ph]

How to get a photon



- 2-body phase space
- Loop factor ~1/16π^2

How to get a photon



- 2-body phase space
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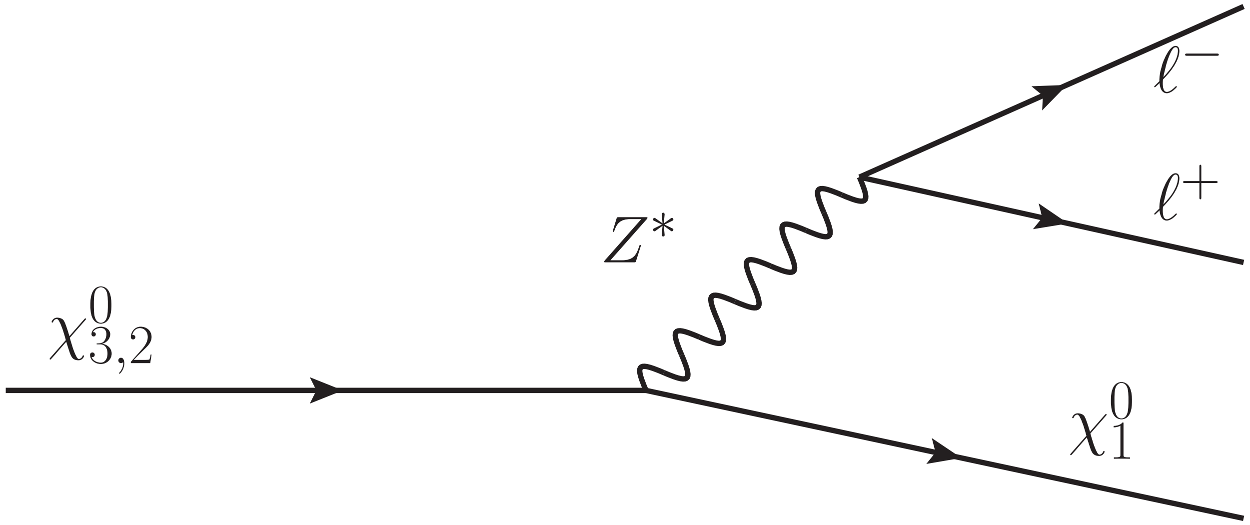
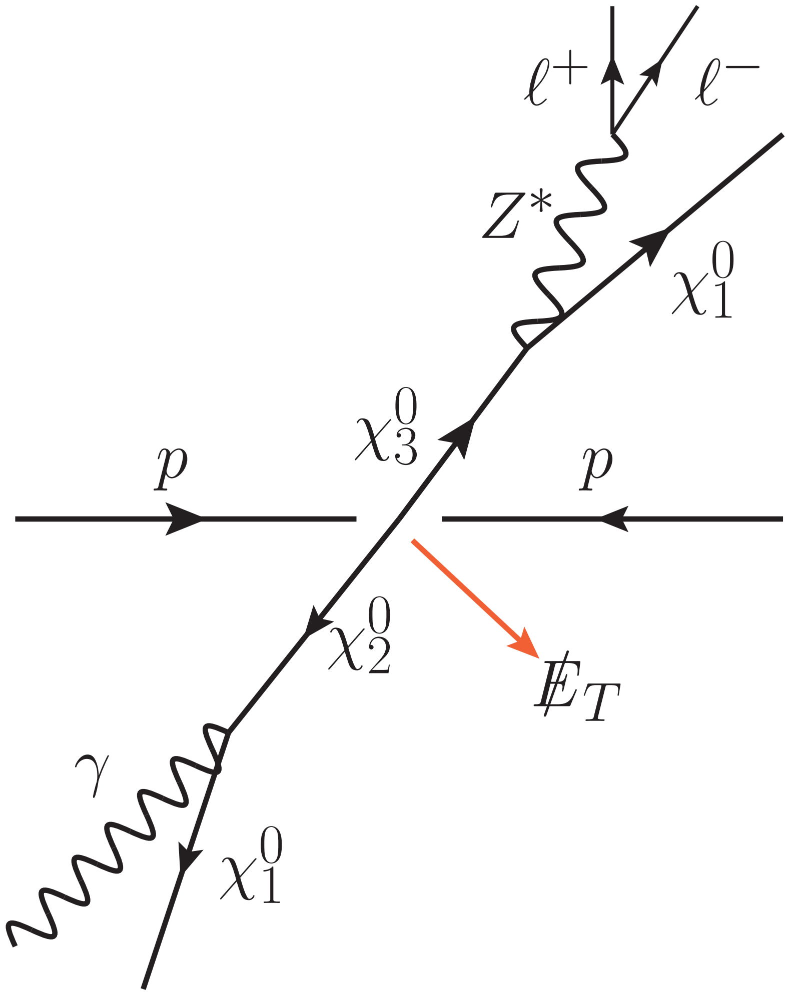


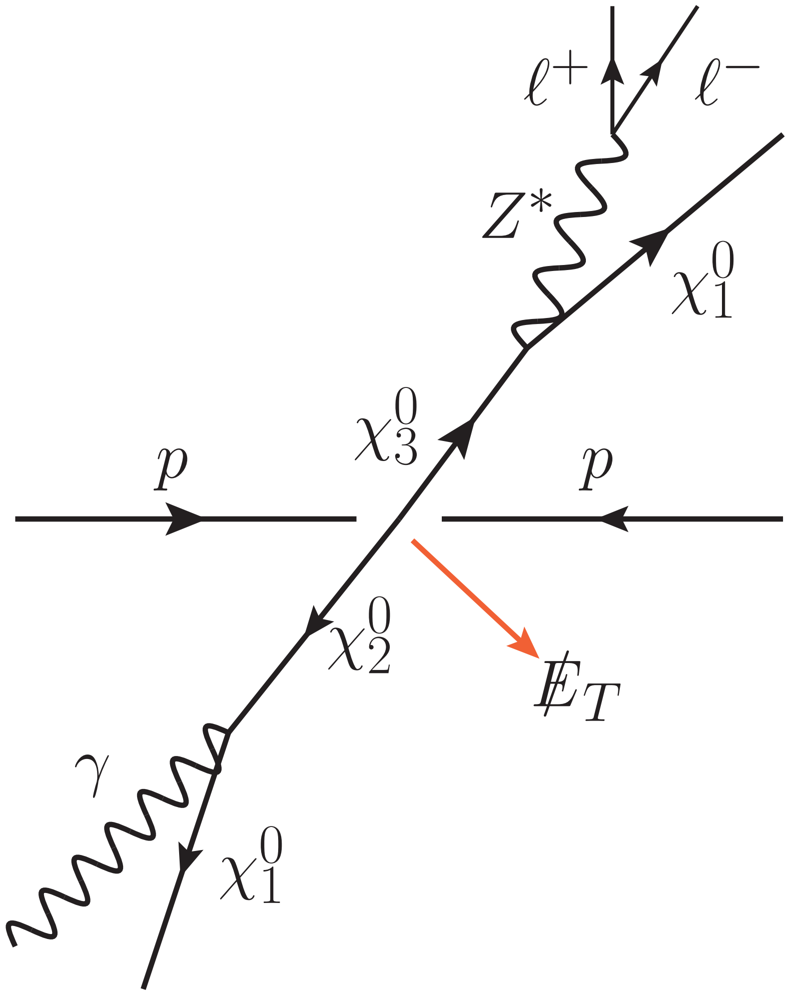
- 3-body phase space ~2BPS * $\frac{1}{(2\pi)^3}\frac{1}{2}\frac{d^3p}{E_p}$
- Z propagator ~ $\frac{1}{p_Z^2 - m_Z^2}$
- BR(Z→l^+l^-)~7%

$pp \rightarrow \chi_2^0 \chi_3^0 \rightarrow \gamma + \ell^+ \ell^- + \not{E}_T$



$pp \to \chi_2^0 \chi_3^0 \to \gamma + \ell^+ \ell^- + \not{E}_T$

Only works in the Bino-Higgsino part of the surface



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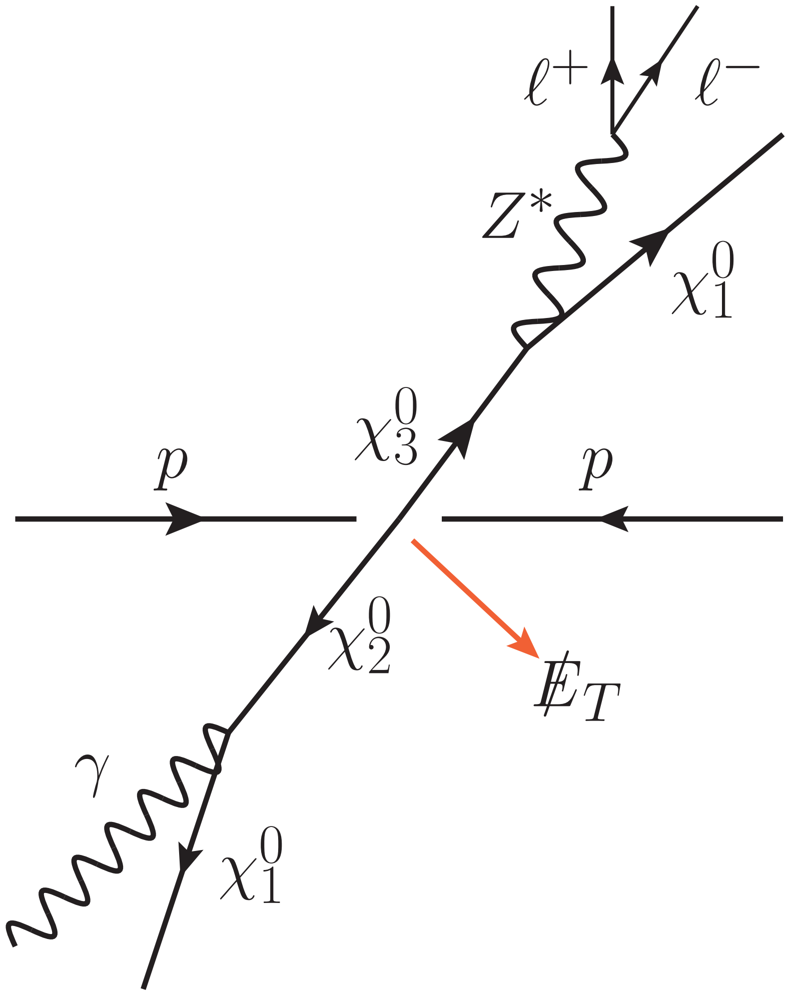
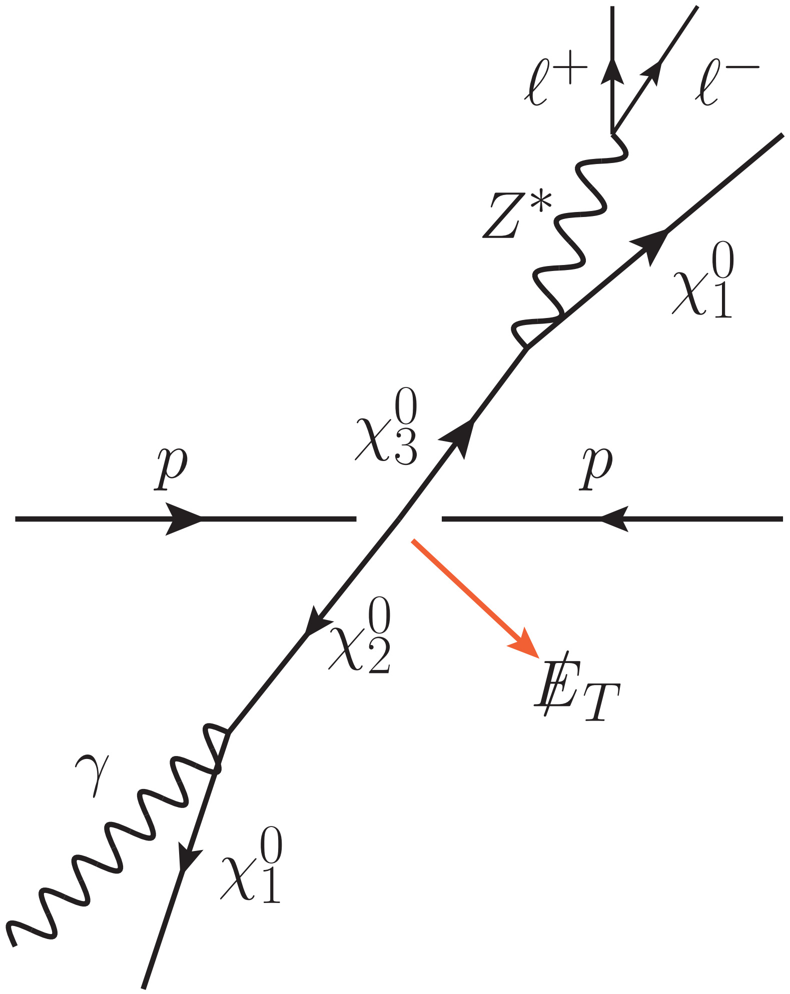


SM Backgrounds

- $\gamma t\bar{t}|_{\text{dilepton}}$
- $\gamma\ \gamma^*/Z(\tau^+\tau^-)|_{\text{dilepton}}$
- $\gamma\ VV|_{\text{dilepton}}$

$$pp \to \chi_2^0\chi_3^0 \to \gamma + \ell^+\ell^- + \cancel{E}_T$$

Only works in the Bino-Higgsino part of the surface



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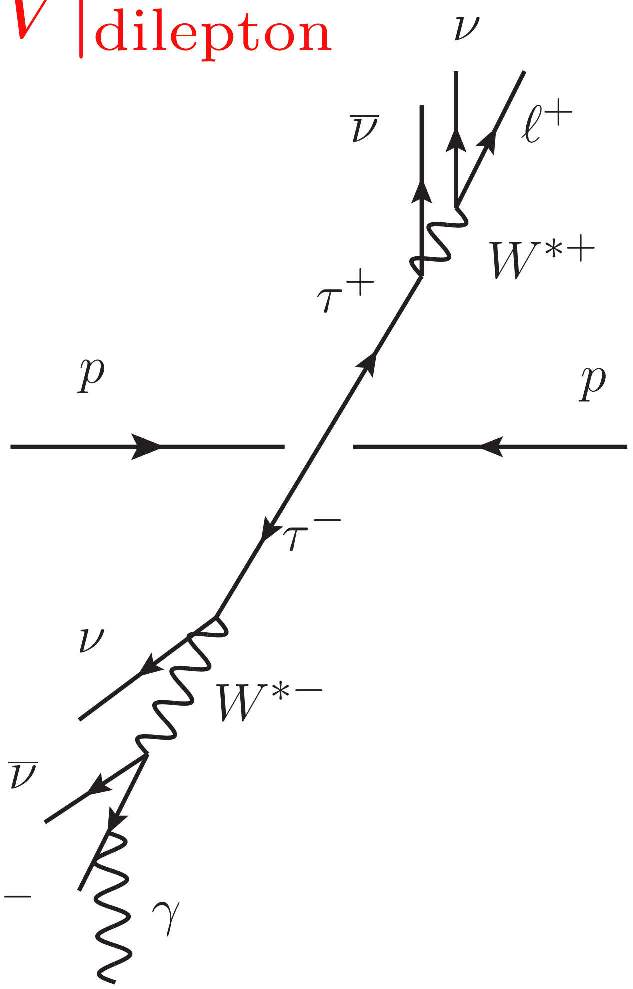

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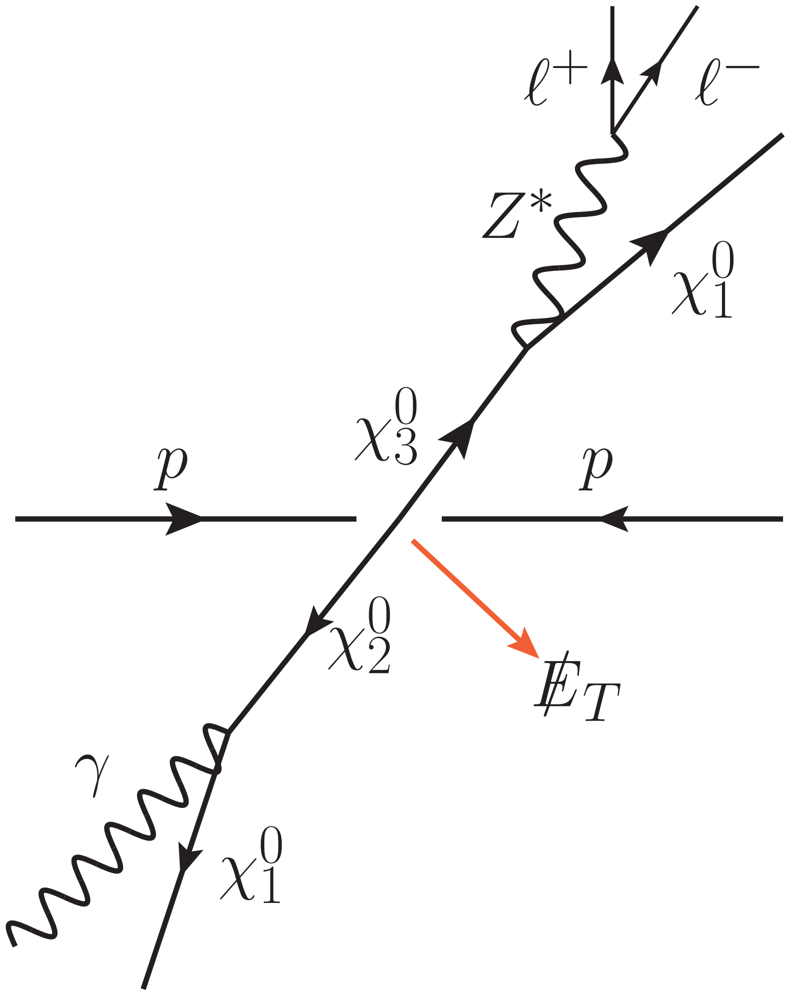

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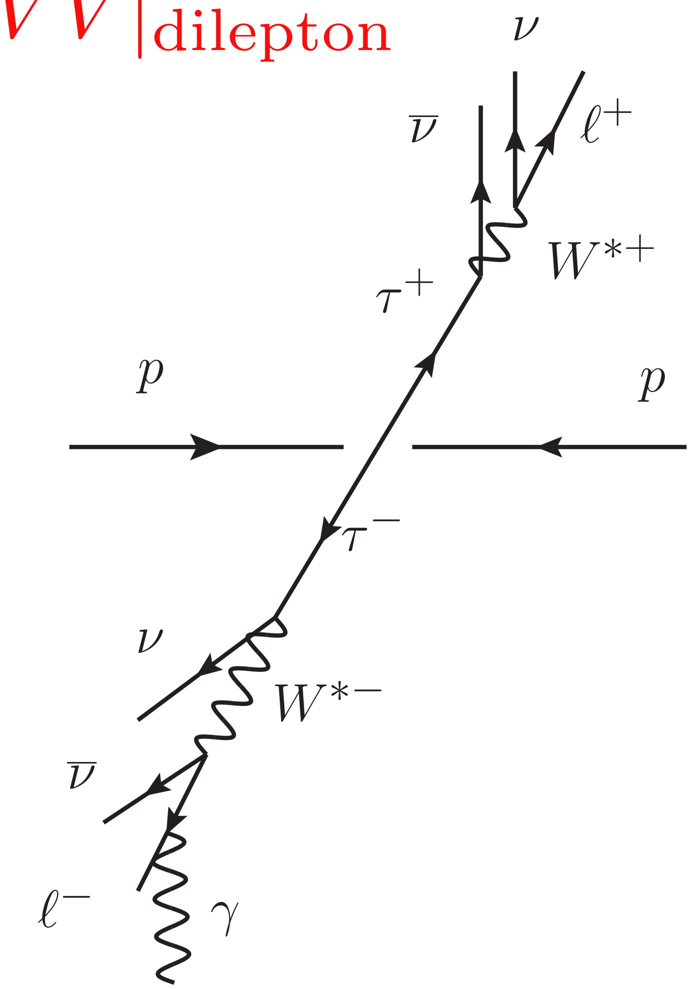
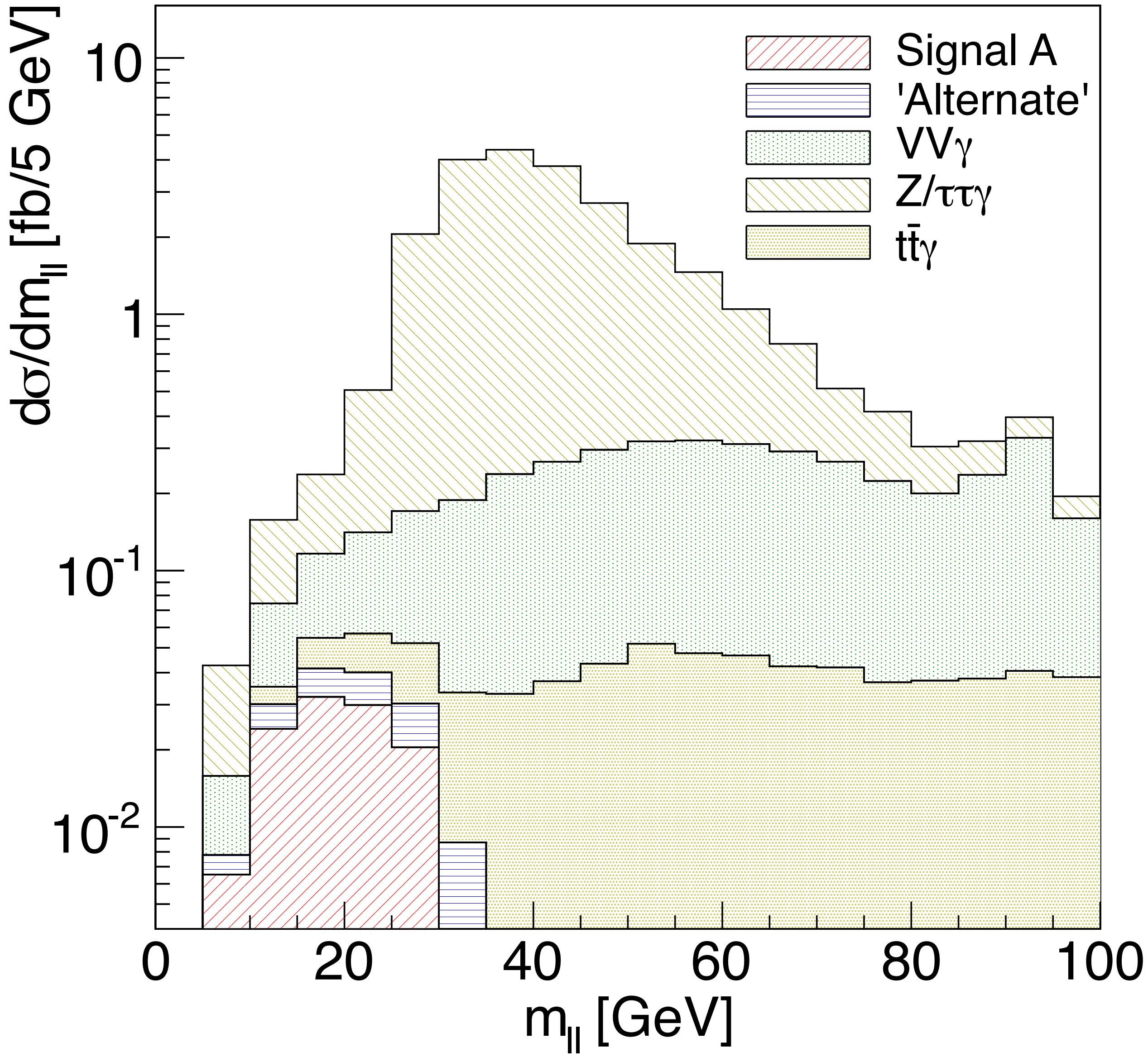
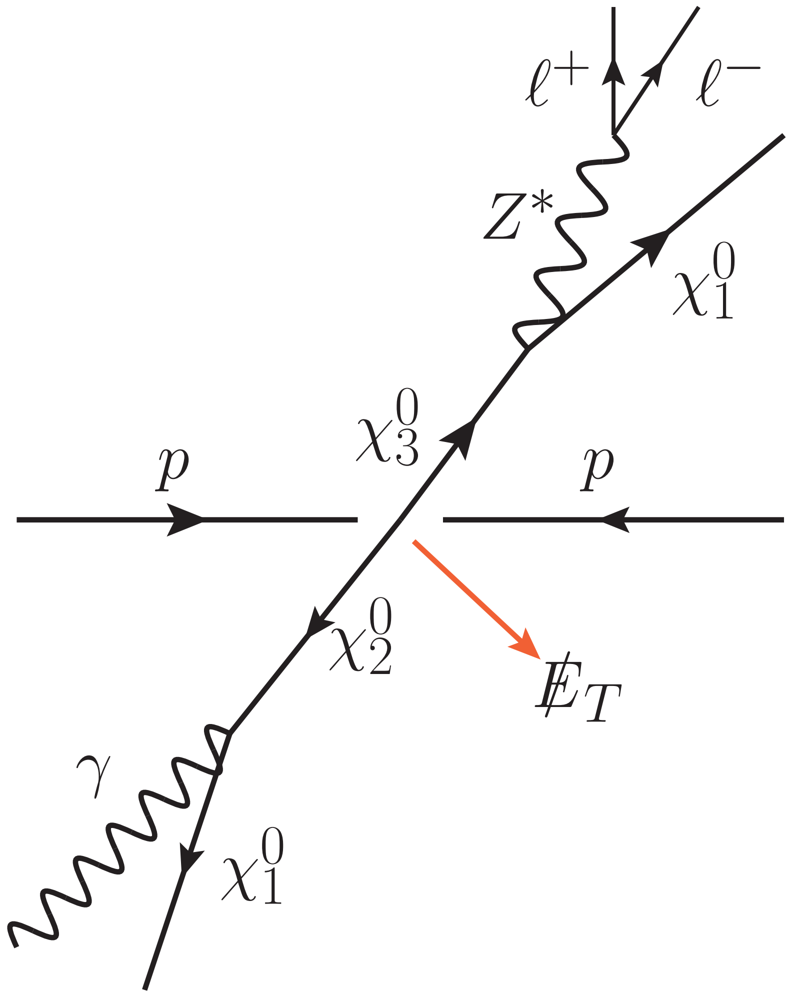


- Angle between leptons
- Transverse mass
- Angle between leptons and photon
- $p_T(\gamma)$, Total MET

$$pp \to \chi_2^0 \chi_3^0 \to \gamma + \ell^+\ell^- + \cancel{E}_T$$

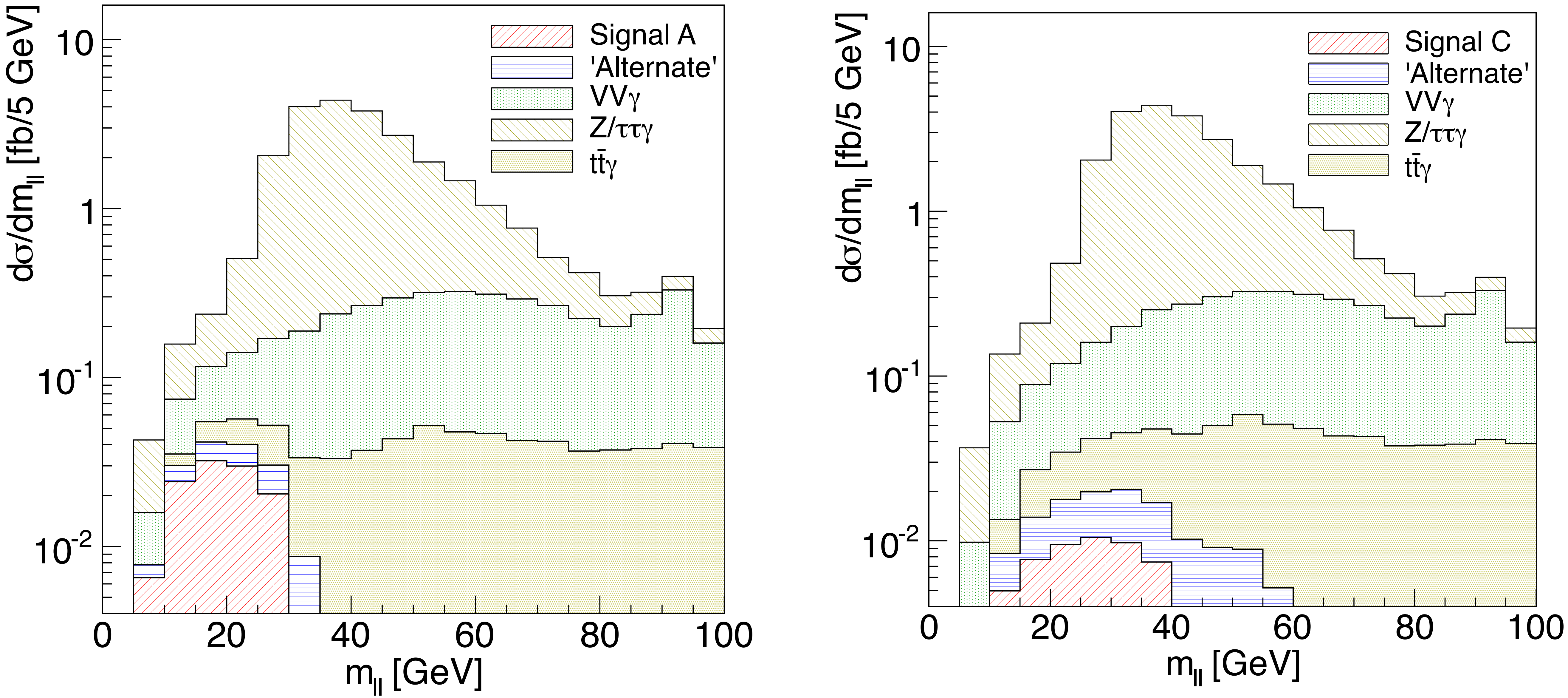
Most discriminating cut is m$_{ll}$





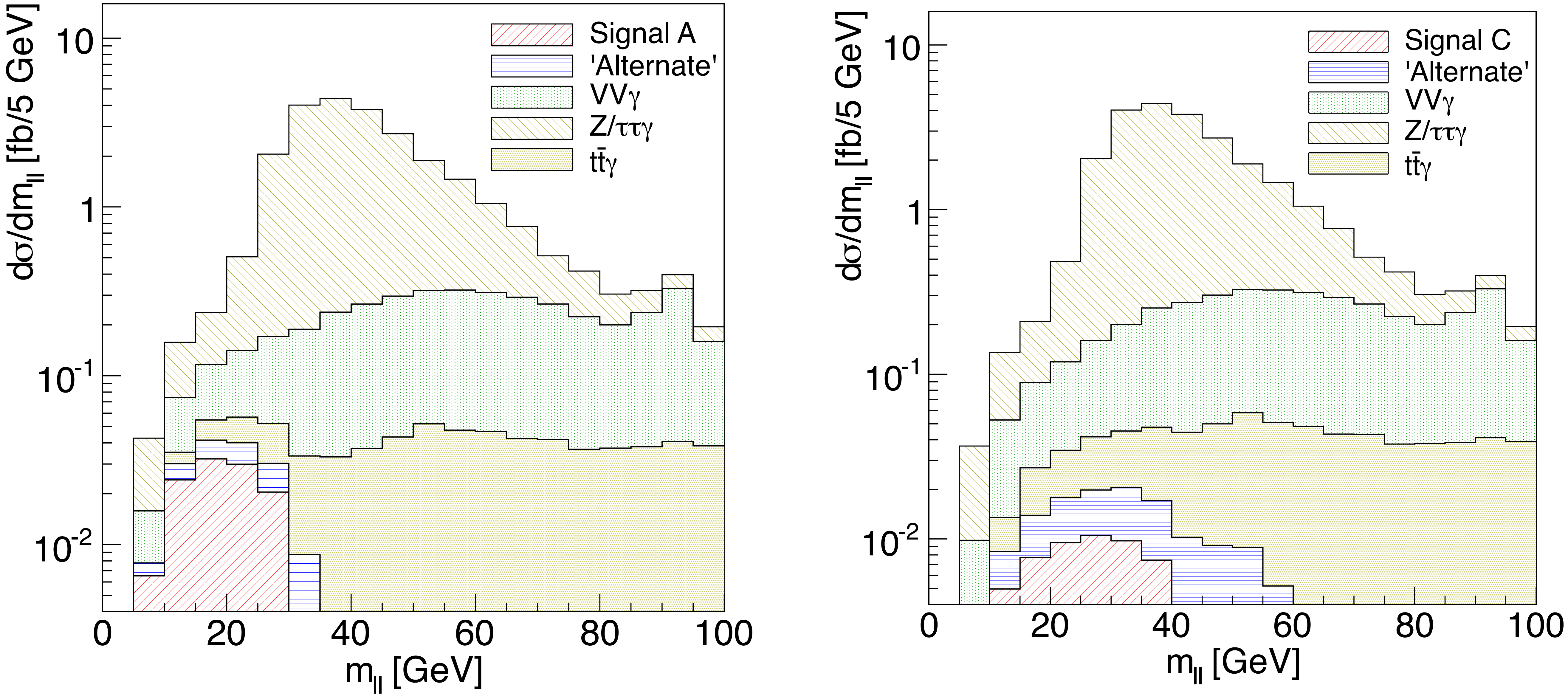
$pp \to \chi_2^0\chi_3^0 \to \gamma + \ell^+\ell^- + \not{E}_T$

Most discriminating cut is m_{ll}



$$pp \to \chi_2^0 \chi_3^0 \to \gamma + \ell^+\ell^- + \not{E}_T$$

Most discriminating cut is m$_{ll}$



*Search cuts are optimal for smaller mass splittings**

$$pp \to \chi_2^0 \chi_3^0 \to \gamma + \ell^+ \ell^- + \not{E}_T$$

Benchmark points	Point A	Point C
μ	-150 GeV	-145 GeV
M_1	125 GeV	120 GeV
$\tan\beta$	2	10
$m_{\tilde{\chi}_1^0}$	124.0 GeV	105 GeV
$m_{\tilde{\chi}_2^0}$	156.9 GeV	150 GeV
$m_{\tilde{\chi}_3^0}$	157.4 GeV	163 GeV
$(\sqrt{s} = 14\ \text{TeV})\ \int \mathcal{L}$ needed $[\text{fb}^{-1}]$	430	4300

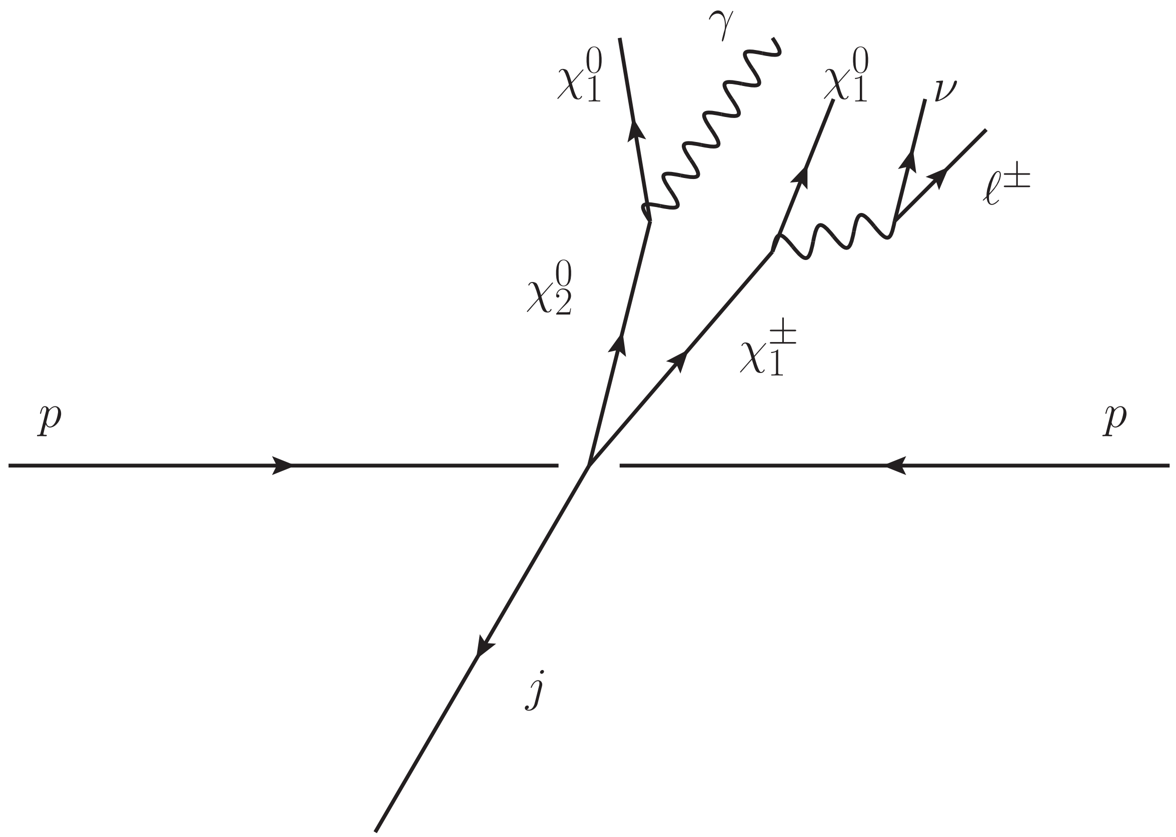
Small mass splitting is good for cuts, bad for triggering

we were using 8-TeV di-lepton trigger, small efficiency

What if the system is boosted off a hard ISR jet to trigger on?

What if the system is boosted off a hard ISR jet to trigger on?

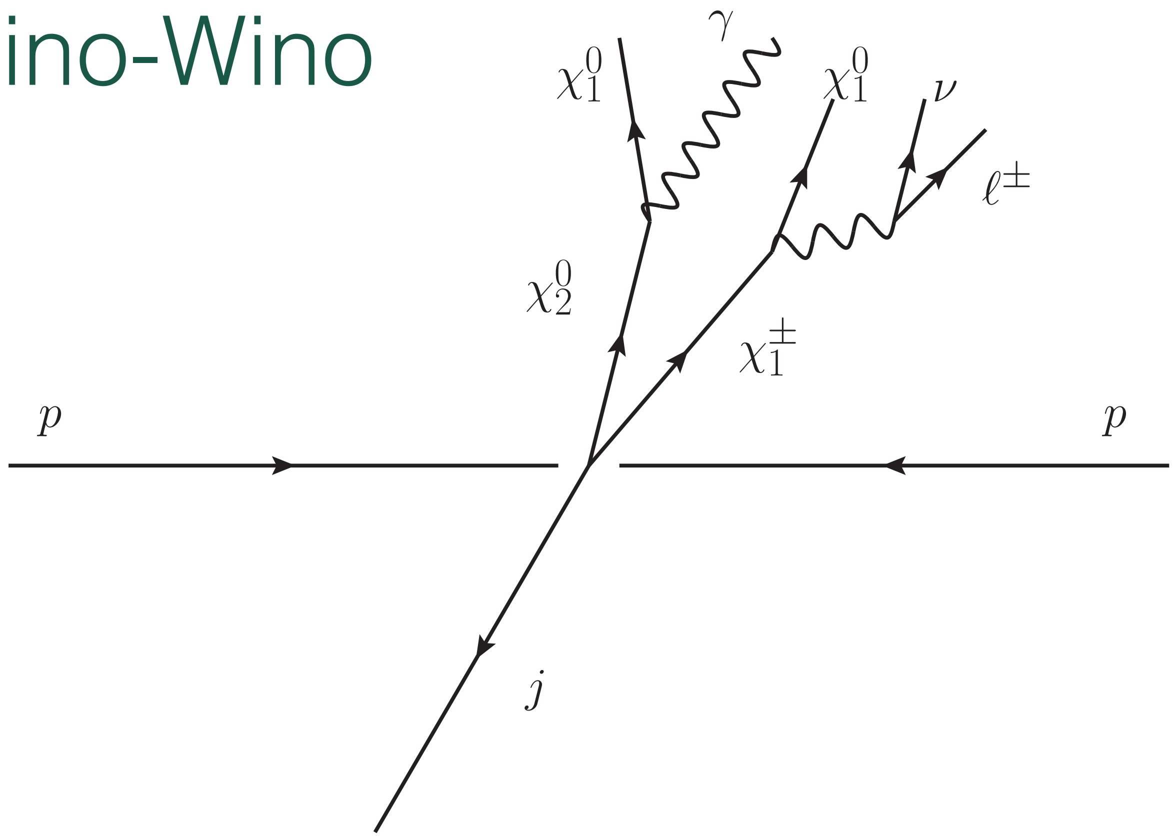
$$pp \rightarrow \chi_2^0 \chi_1^+ \rightarrow \gamma + \ell^+ + \not{E}_T$$



What if the system is boosted off a hard ISR jet to trigger on?

$$pp \to \chi_2^0\chi_1^+ \to \gamma + \ell^+ + \not{E}_T$$

Bino-Wino



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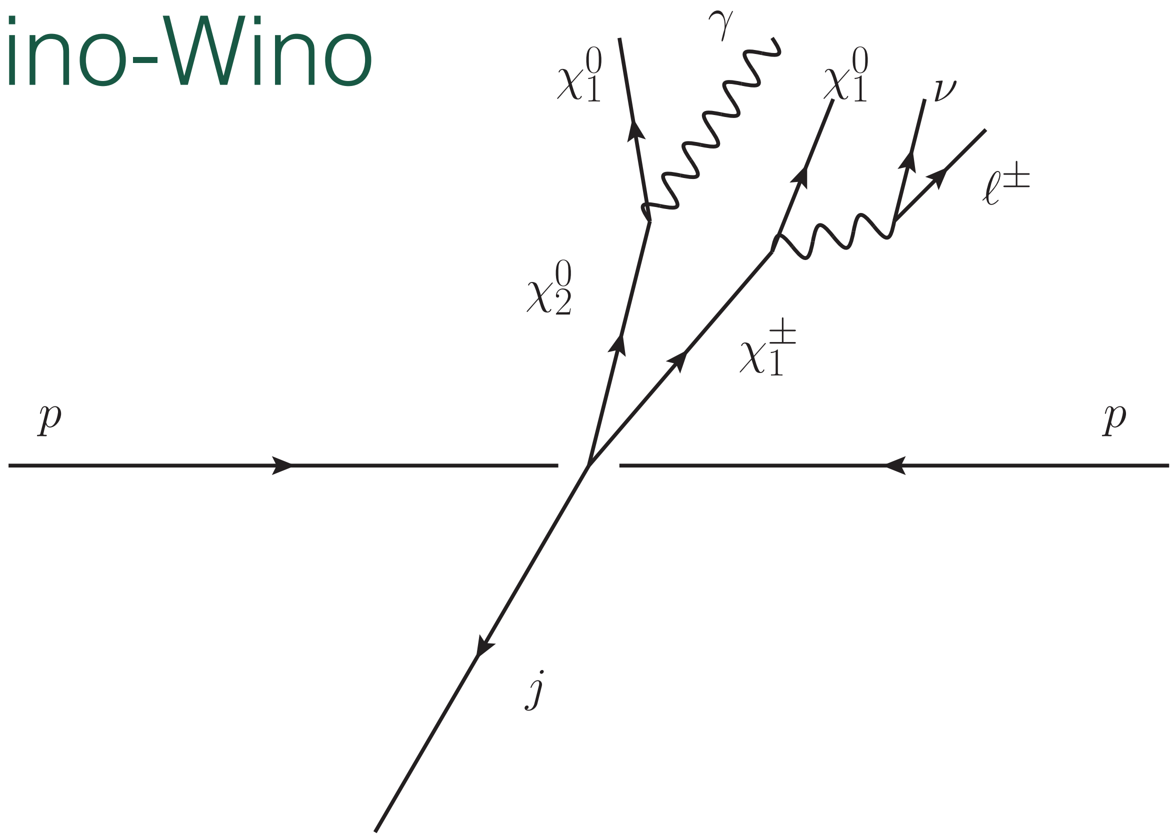

- $\not{E}_T \propto p_T(j)$
- $p_T(\gamma) \propto \Delta(m_{\chi_2^0}, m_{\chi_1^0})$
- $p_T(\ell) \propto \Delta(m_{\chi_1^\pm}, m_{\chi_1^0})$

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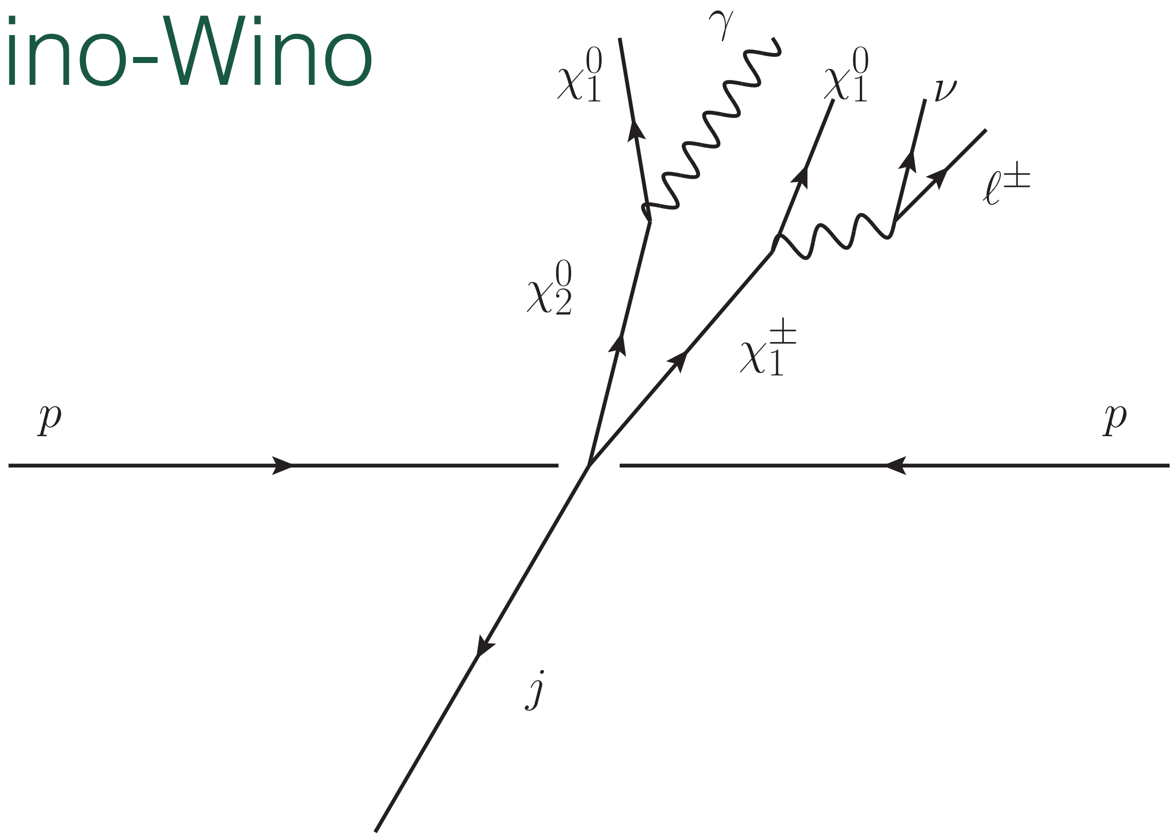
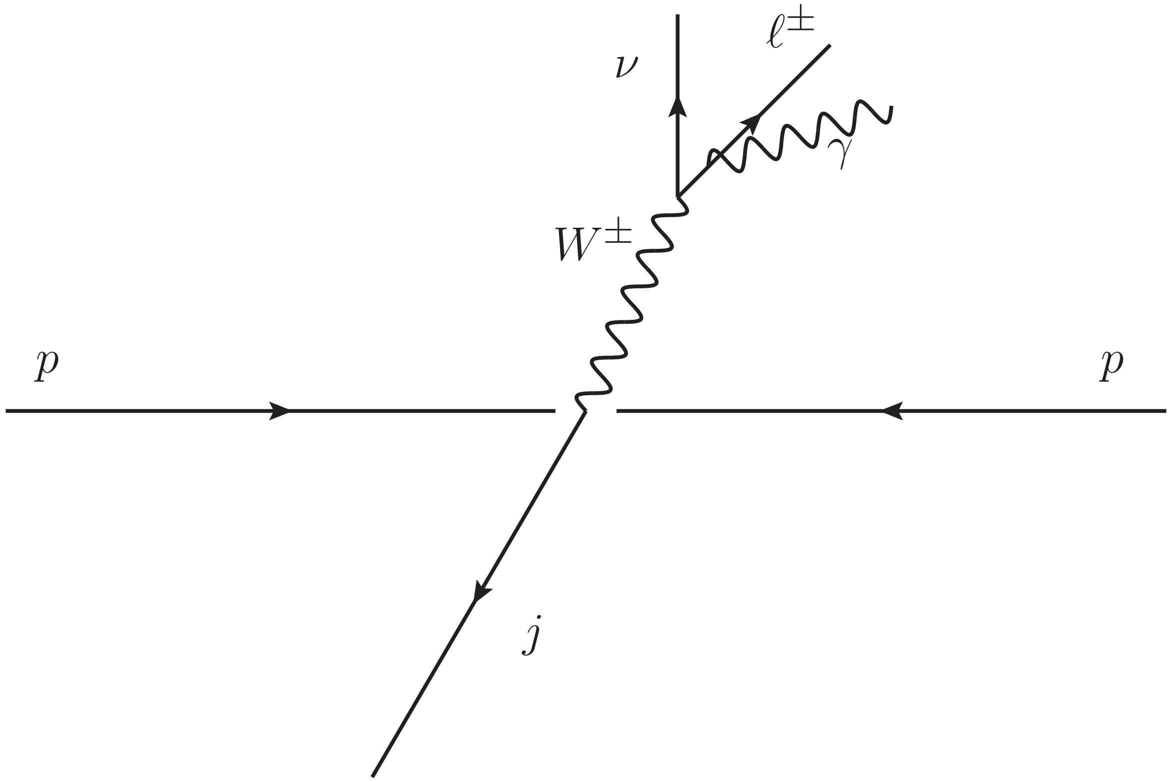


Dominant Background



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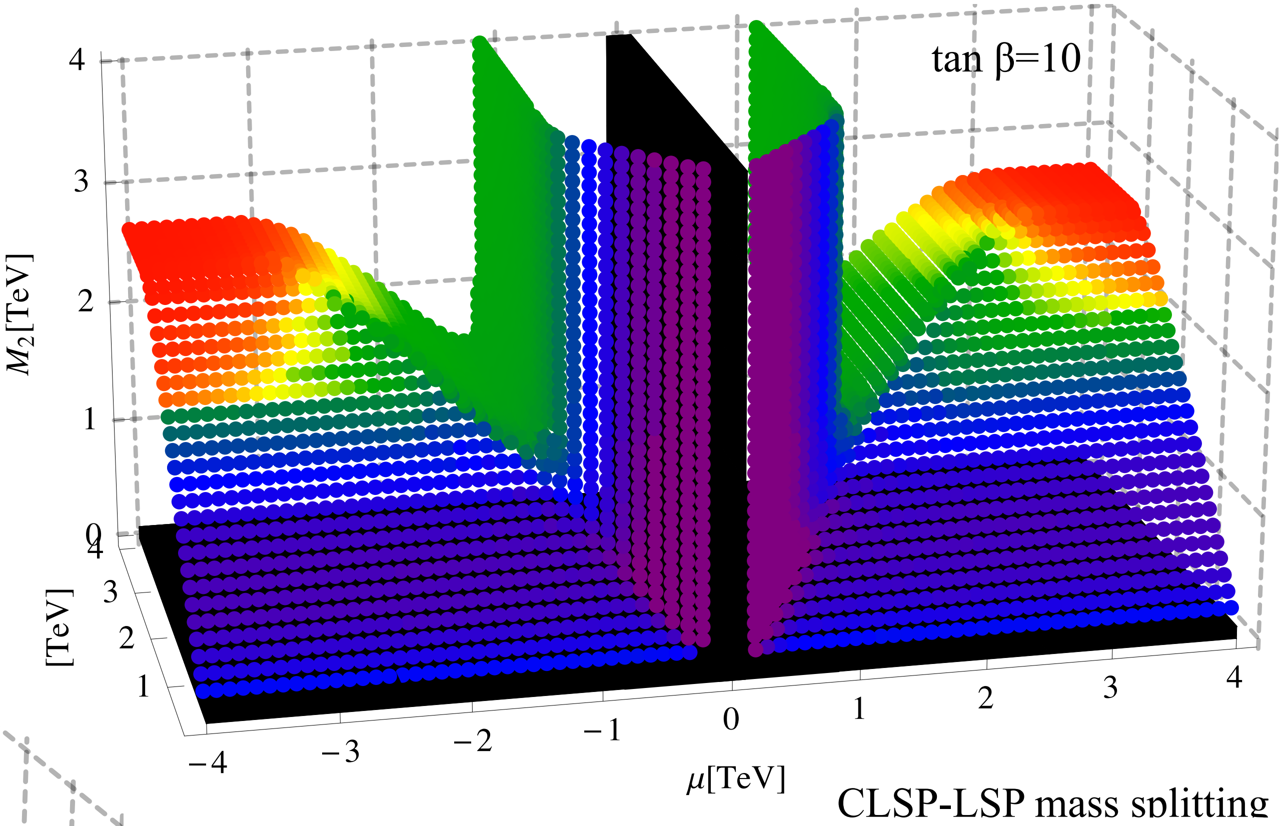
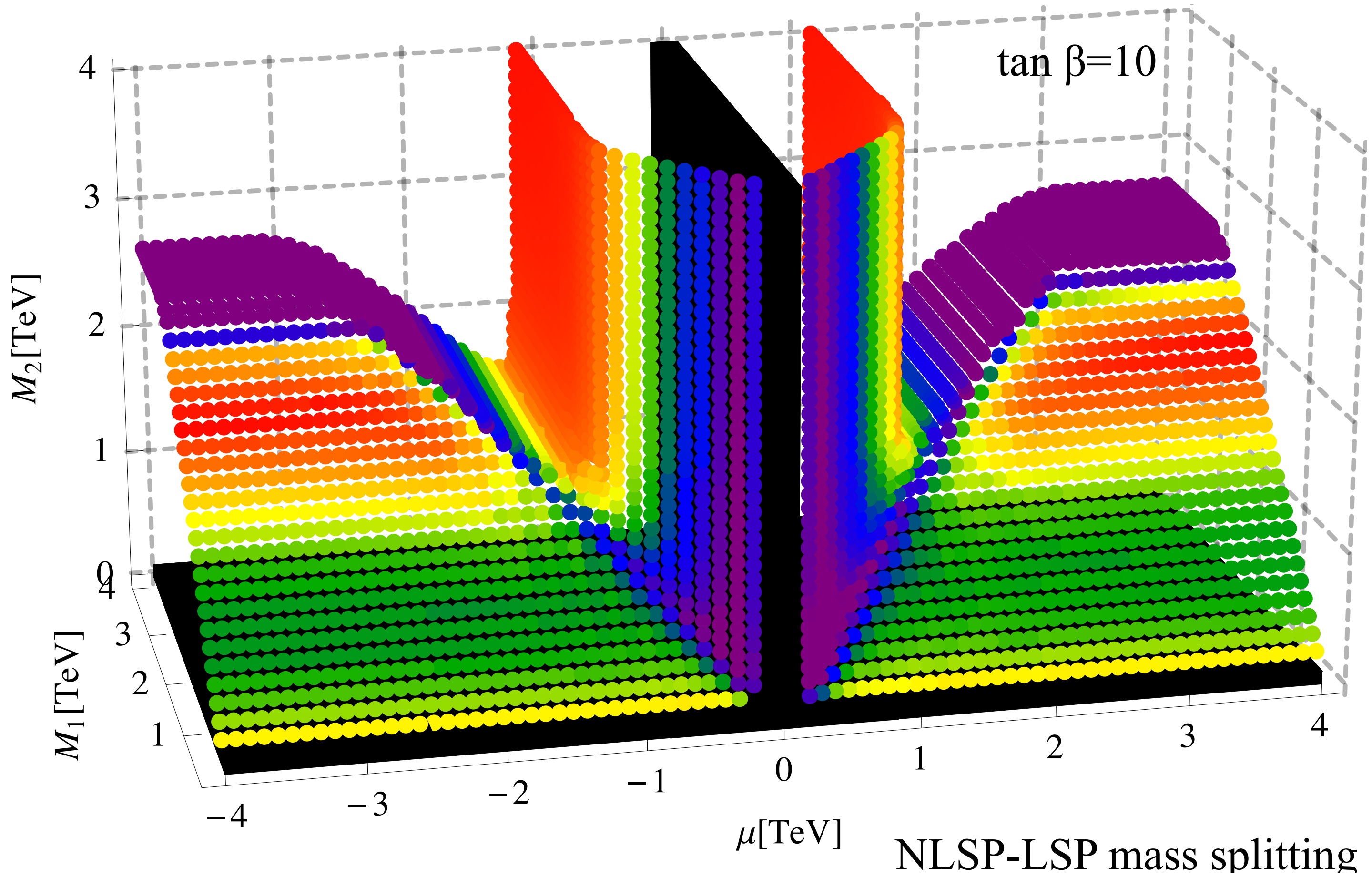
- $\not{E}_T \propto p_T(j)$
- $p_T(\gamma) \propto p_T(j)$
- $p_T(\ell) \propto p_T(j)$

Parameter space for $pp \to \chi_2^0 \chi_1^+ \to \gamma + \ell^+ + \not{E}_T$

CLSP-LSP mass splitting

$m_{\chi_1^\pm}$-$m_{\chi_1^0}$= ●<0.15 |●0.25 |●0.35 |●1 |●20 |●>40 GeV





NLSP-LSP mass splitting

$m_{\chi_2^0}$-$m_{\chi_1^0}$= ●<1 |●10 |●20 |●30 |●40 |●>60 GeV

$pp \to \chi_2^0 \chi_1^+ \to \gamma + \ell^+ + \not{E}_T$

Larger $p_T(j)$ yields more separation from background

$pp \to \chi_2^0 \chi_1^+ \to \gamma + \ell^+ + \not{E}_T$

Larger $p_T(j)$ yields more separation from background

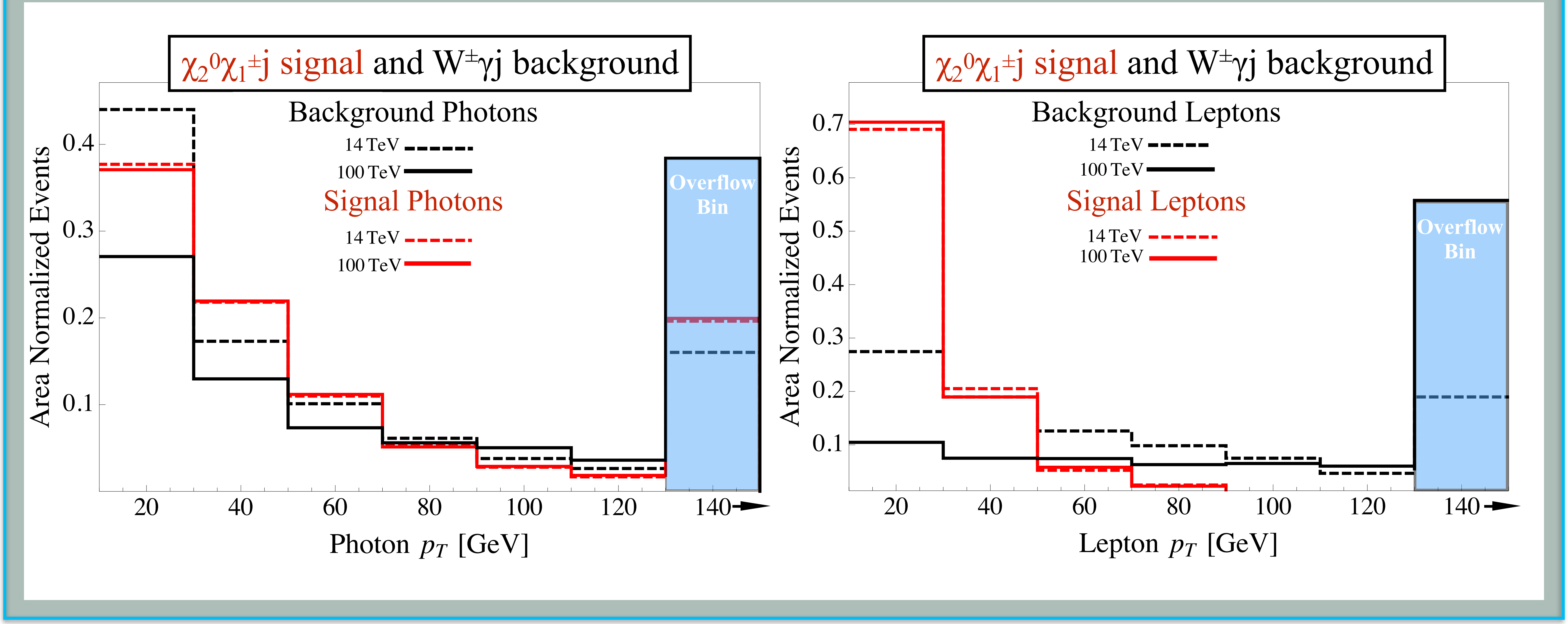
Higher Energy Collider

$pp \to \chi_2^0 \chi_1^+ \to \gamma + \ell^+ + \not{E}_T$

Larger $p_T(j)$ yields more separation from background

Higher Energy Collider

$$m_{\chi_2^0} = m_{\chi_1^\pm} = 200 \text{ GeV}; m_{\chi_1^0} = 190 \text{ GeV}$$
$$p_T(j) > 100(600) \text{ GeV}$$



$pp \to \chi_2^0 \chi_1^+ \to \gamma + \ell^+ + \not{E}_T$ Results

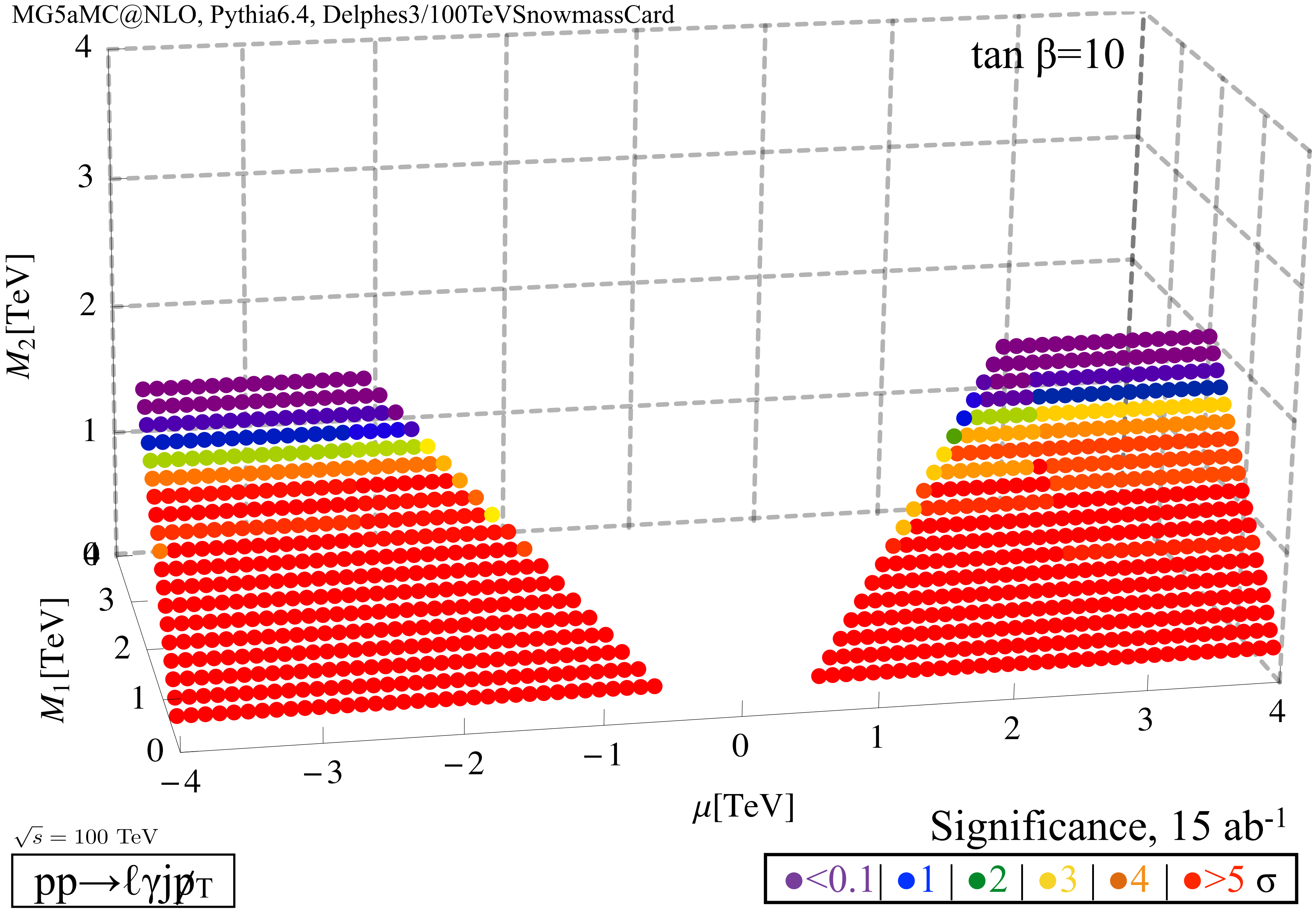
$p_{T,j} > 0.8$ TeV $|\eta_j| < 2.5$

$\not{E}_T > 1.2$ TeV

$p_{T,\ell} = [10 - 60]$ GeV $|\eta_\ell| < 2.5$

$p_{T,\gamma} = [10 - 60]$ GeV $|\eta\gamma| < 2.5$

$M_{T2}^{\gamma,\ell} < 10$ GeV $\Delta R_{\ell\gamma} > 0.5$



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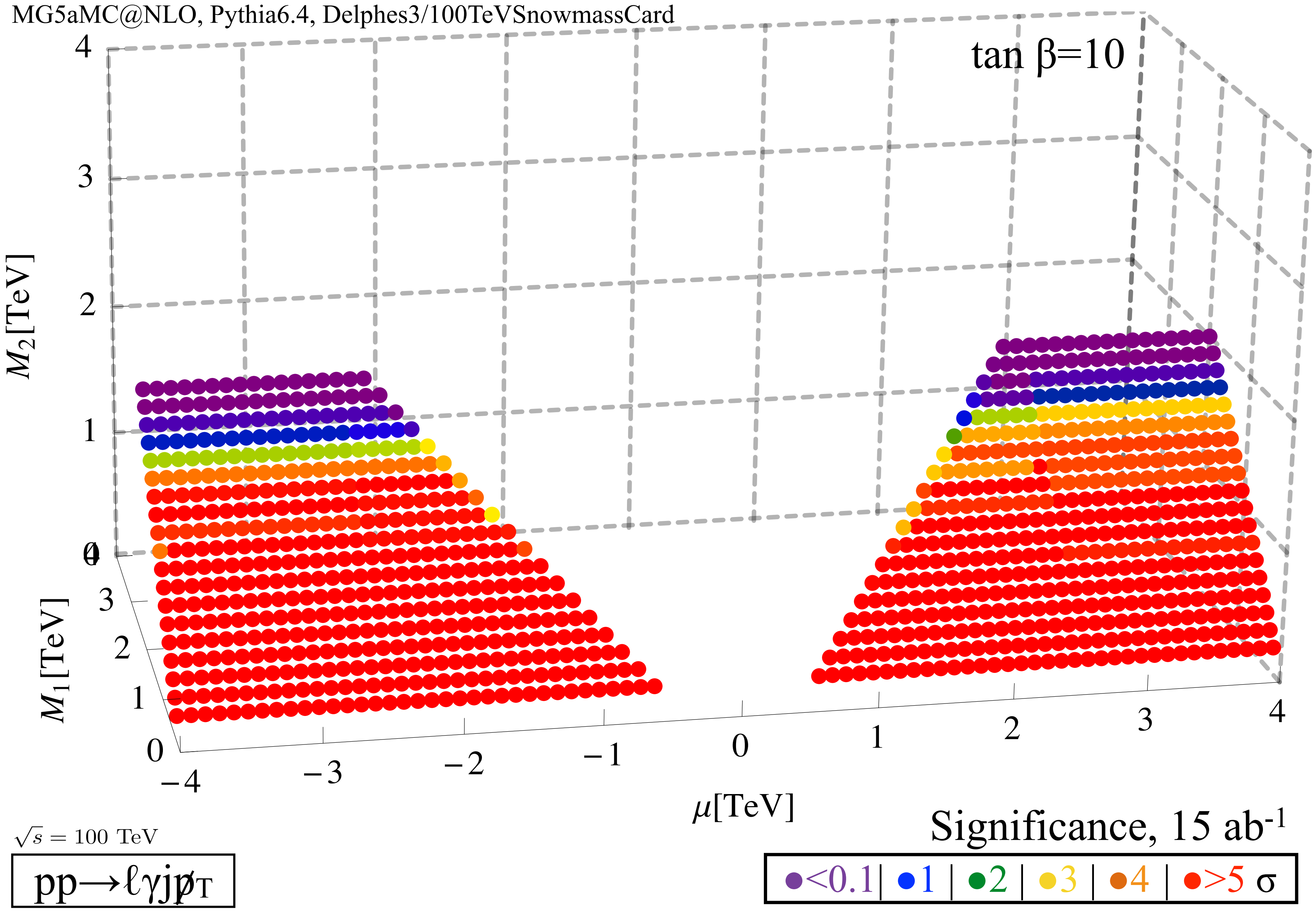

Cover most of the Bino-Wino plane!

Where are we going?

Can entire surface be discovered with current/future experiments?

- Examine Direct/Indirect Detection constraints
- Explore search techniques at high energy colliders

❒ Cover Bino-Wino surface
❒ Resolve conflicts with pure wino

- Complementarity between experiments

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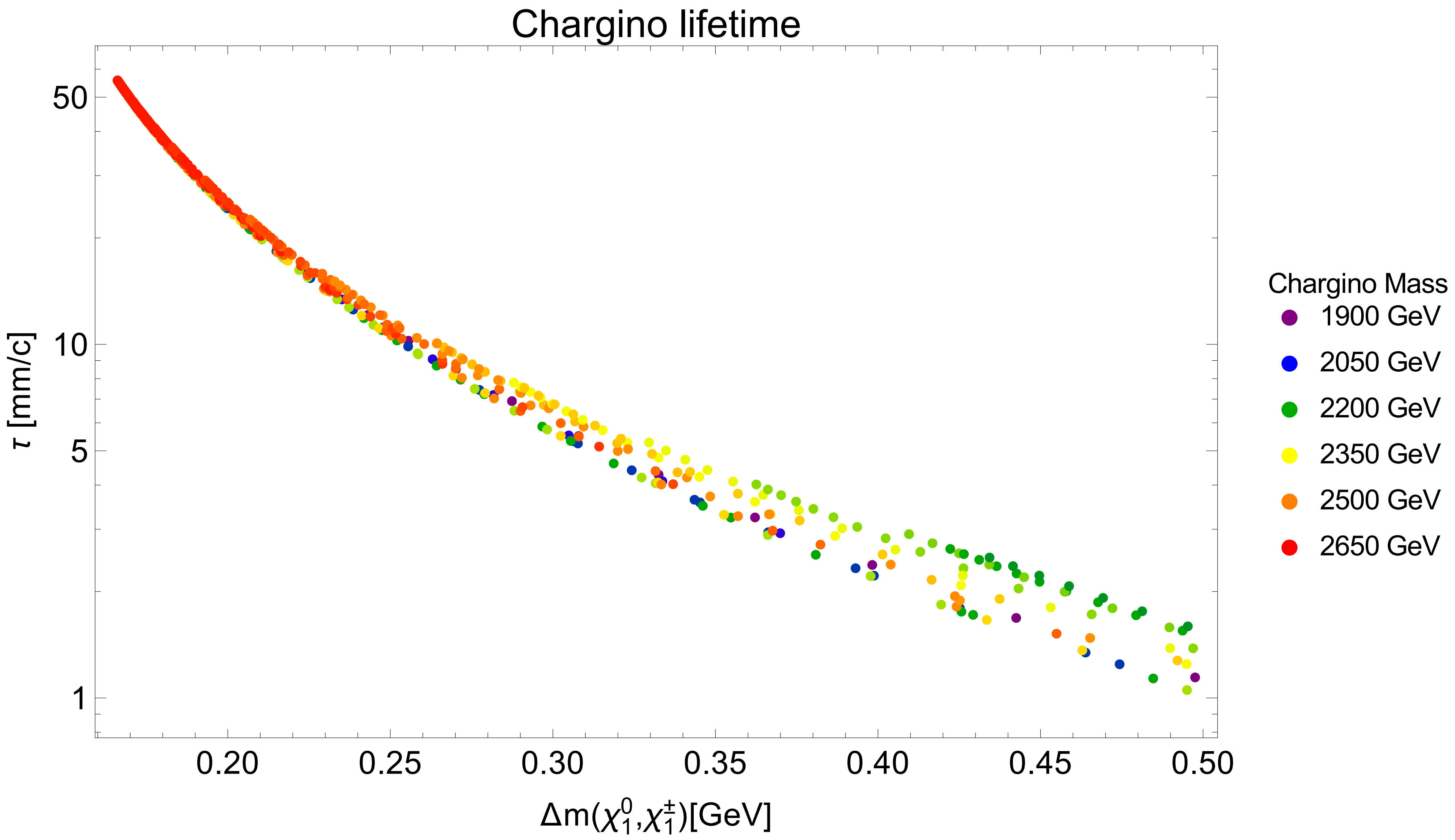
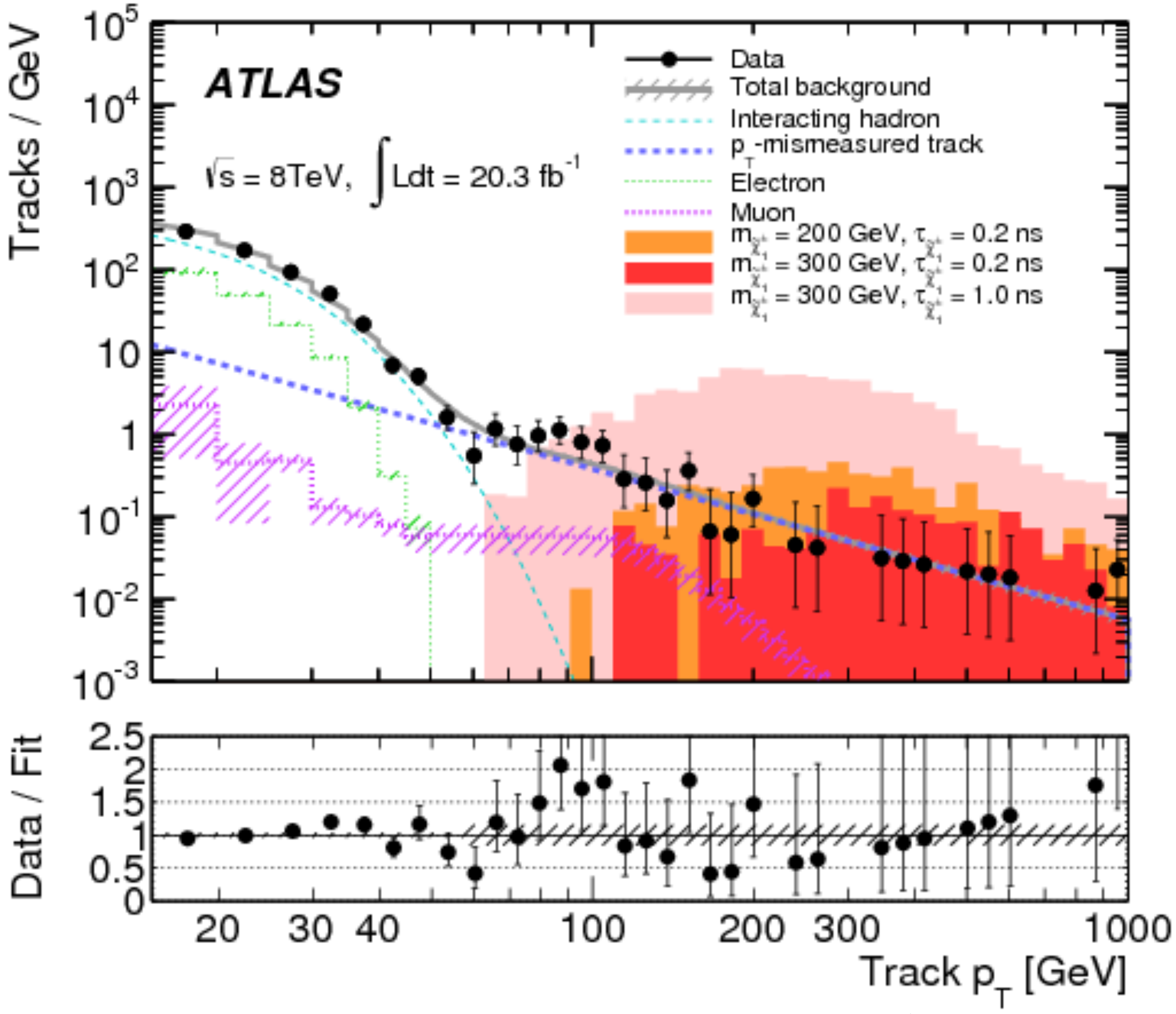
Resolve conflicts with pure wino

- Pure Wino mass splittings come at loop level
- Small mass splitting → little phase space → large lifetimes
- Look for chargino traveling a macroscopic distance then decaying to pions (soft and undetected). i.e. ***disappearing track***



Disappearing Track

What process gives a background for a disappearing track?



$$p_{T,j} > 90\ \text{GeV},\quad \not{E}_T > 90\ \text{GeV},\quad \Delta\phi_{min}^{\text{jet}-E_T^{\text{miss}}} > 1.5$$

Isolated track (with largest p_T) with
30 cm < L_T < 80 cm

- At large p_T dominated by p_T mismeasured tracks
- Fit by p_T^{-a} with $a=1.78\pm0.05$

Extrapolation

- Assume same shape
- Scale total background @ 8 TeV to ratio of

$$pp \to \nu\bar{\nu} + j$$

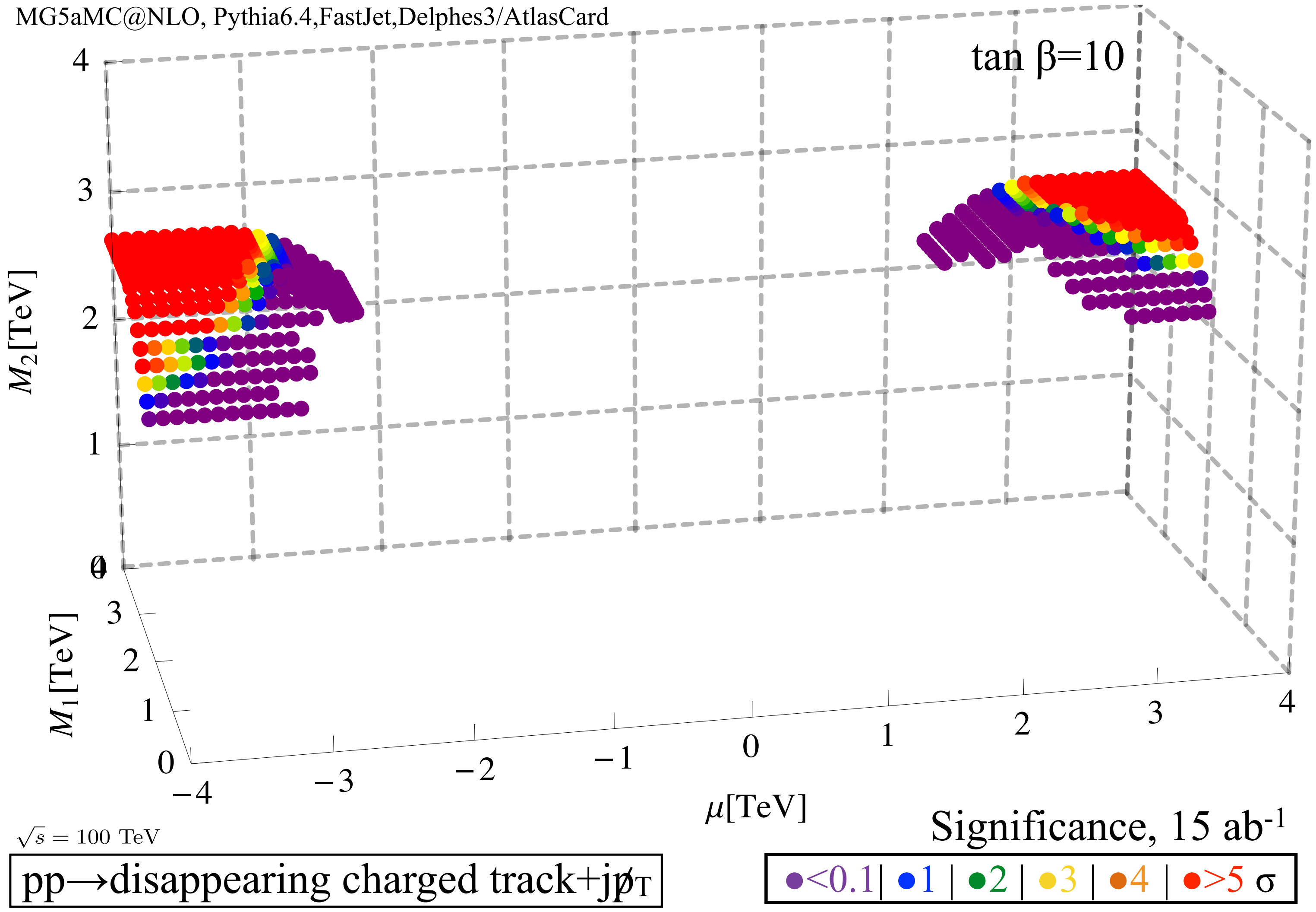
between 100 TeV/8 TeV
- Same detector size

Disappearing Track

$$p_{T,j} > 1\text{ TeV},\quad \not{E}_T > 1.4\text{ TeV},\quad \Delta\phi_{min}^{\text{jet}-E_T^{\text{miss}}} > 1.5$$

$$p_{T,j_2} > 500\text{ GeV},\qquad p_{T,\text{track}} > 2.1\text{ TeV}$$

Isolated track (with largest p_T) with 30 cm < L_T < 80 cm



M. Low and L. T. Wang, JHEP **1408**, 161 (2014) [arXiv:1404.0682 [hep-ph]].
M. Cirelli, F. Sala and M. Taoso, JHEP **1410**, 033 (2014) [JHEP **1501**, 041 (2015)] [arXiv:1407.7058 [hep-ph]]

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  ☑ Cover Bino-Wino surface
  ☑ Resolve conflicts with pure wino

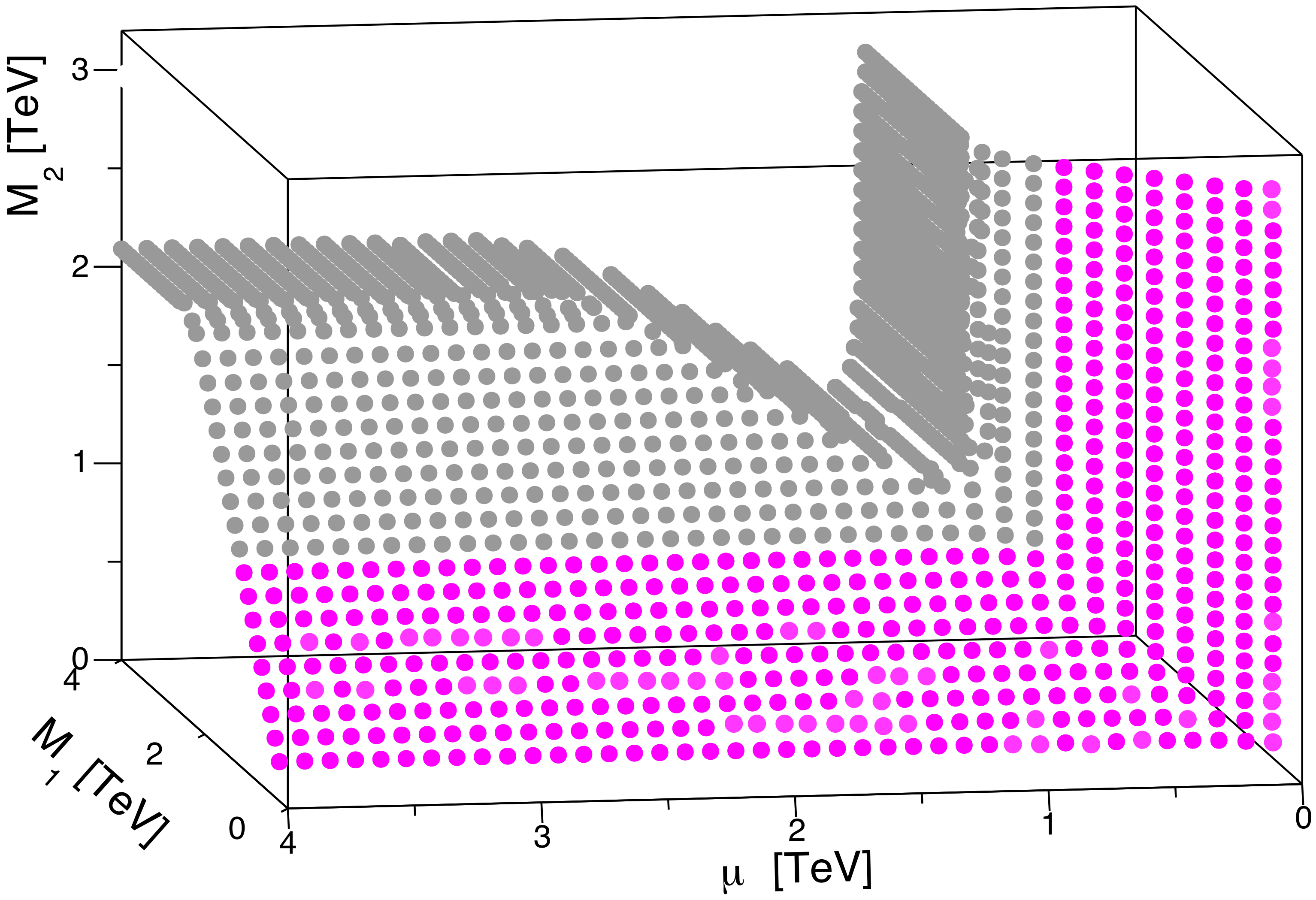
- Complementarity between experiments

More soft objects in energetic events

Extend methodology of the j+γ+$l^{\pm}$ search to soft dileptons

$$p_{T,\ell} = [10 - 50]\ \text{GeV},\quad p_{T,j} > 100\ \text{GeV},$$
$$m_{\ell\ell} < m_{\ell\ell}^{\text{max}},\quad \not{E}_T > 500\ \text{GeV}$$

Relic neutralino 5σ discovery with soft dileptons (3 ab^{-1})



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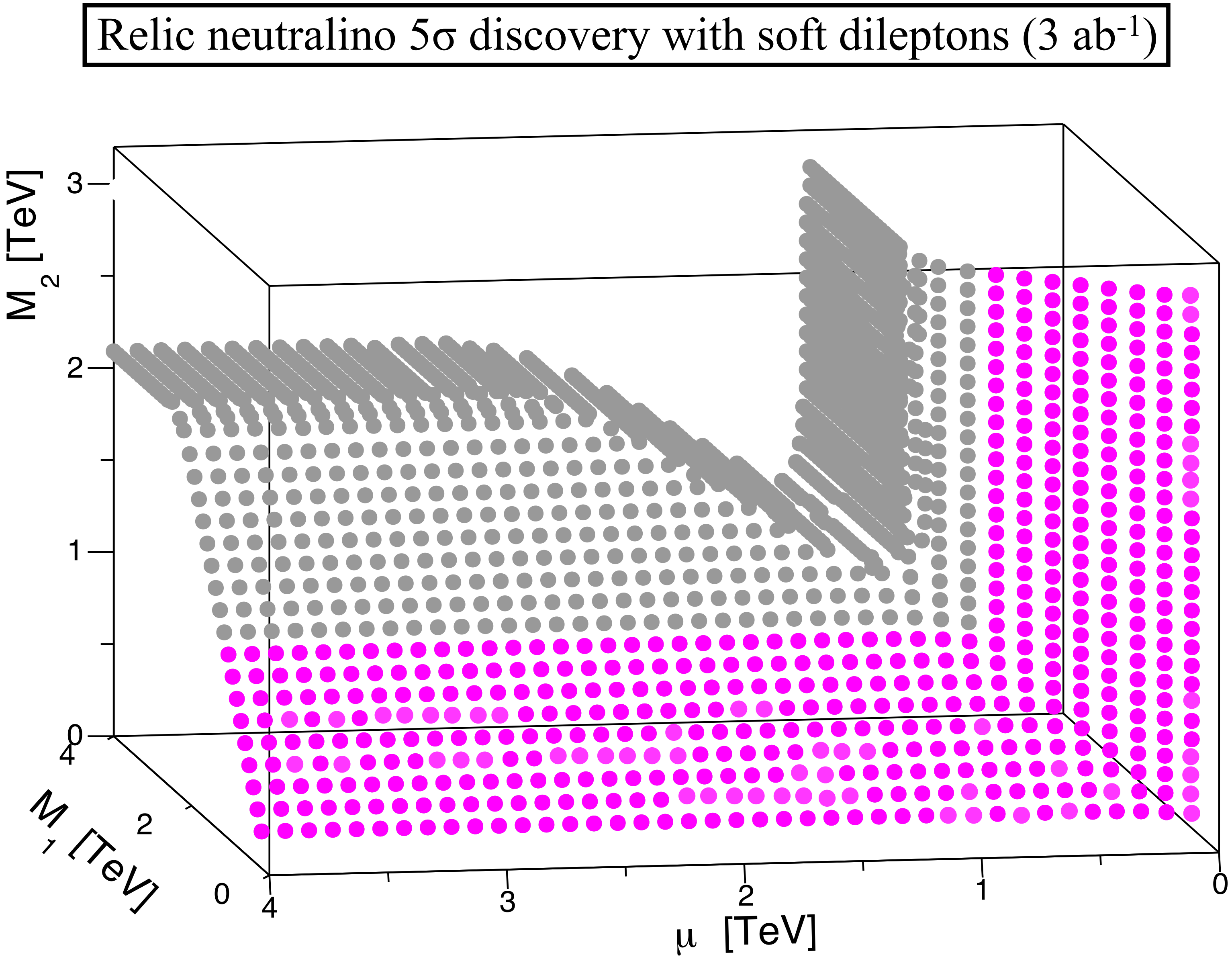
Relic neutralino 5σ discovery with soft dileptons (3 ab^{-1})

Soft dileptonic decay of χ_2^0 allows for discovery of much of Bino-Higgsino and some Bino-Wino

Where are we going?

Can entire surface be discovered with current/future experiments?

- Examine Direct/Indirect Detection constraints
- Explore search techniques at high energy colliders
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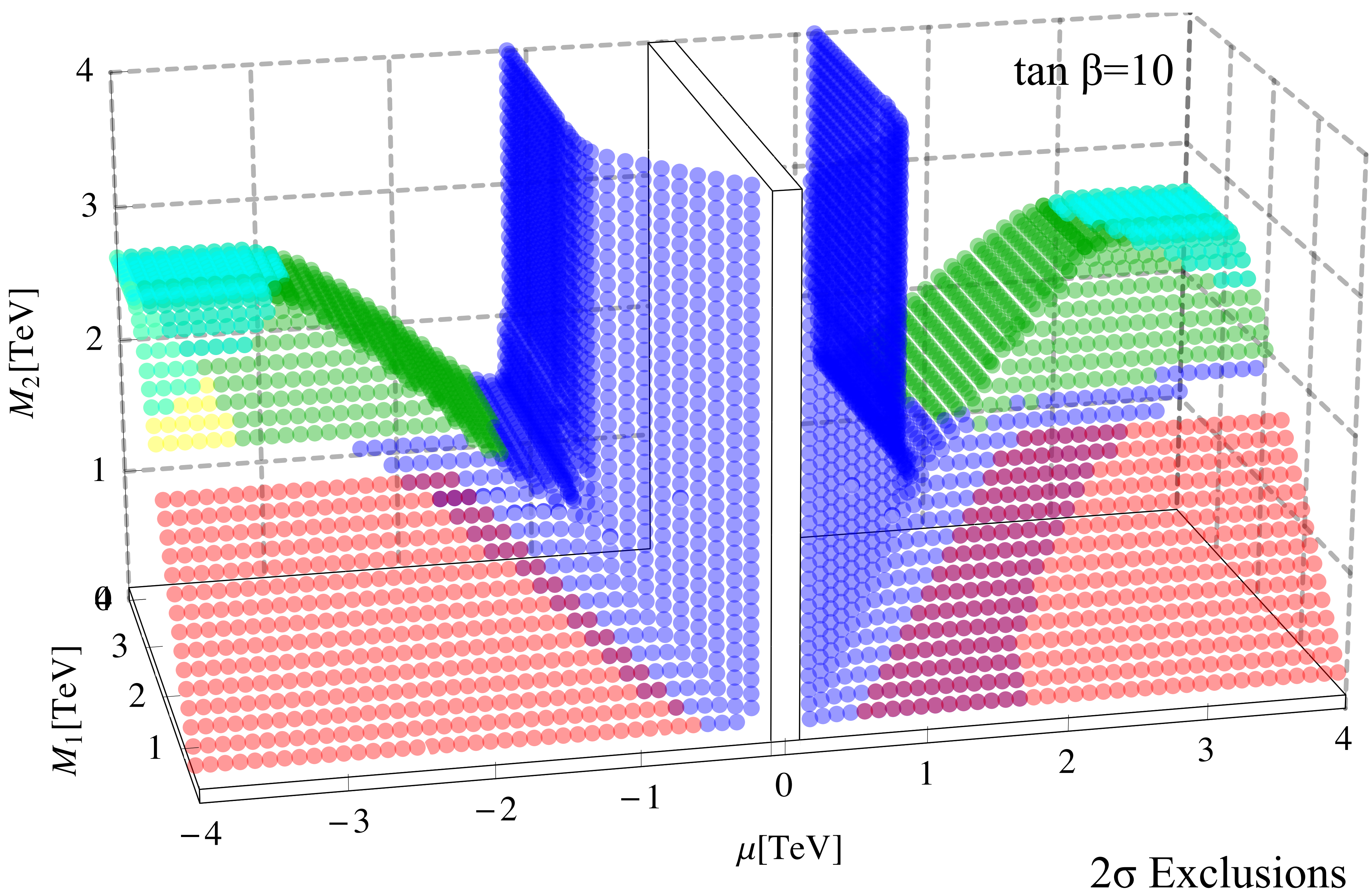
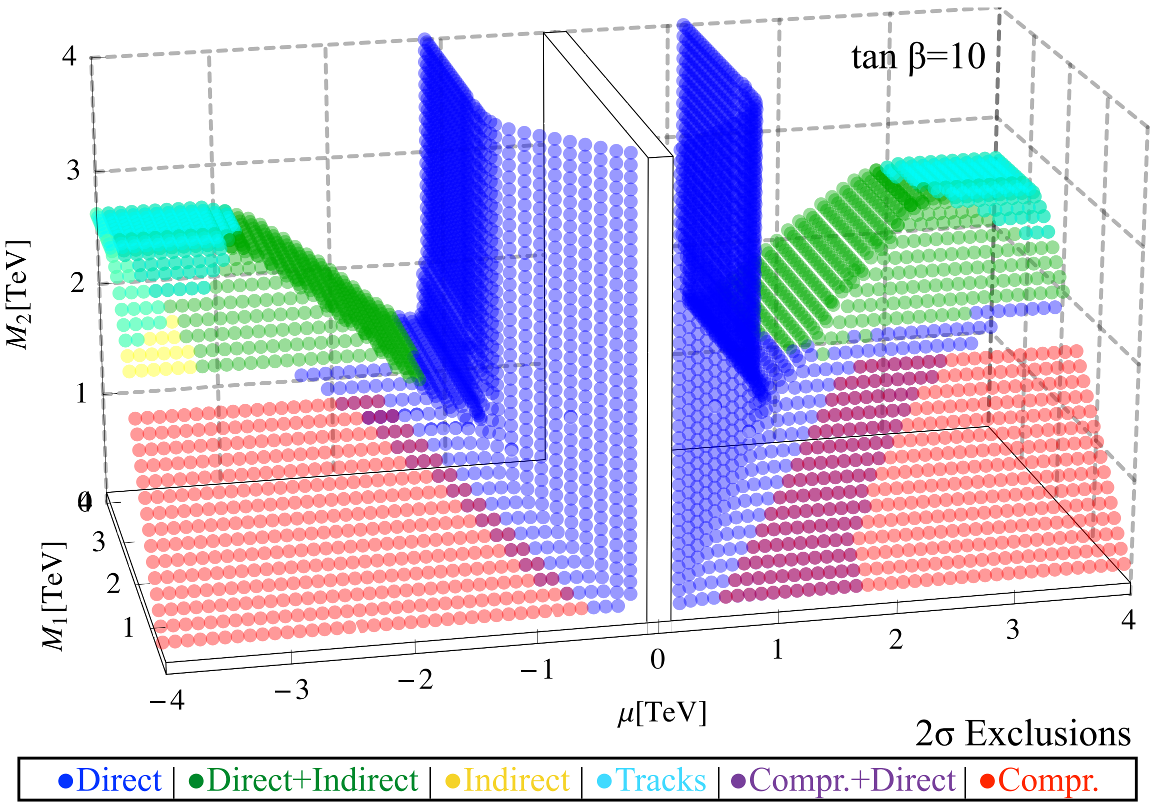
Putting the searches together



●Direct | ●Direct+Indirect | ●Indirect | ●Tracks | ●Compr.+Direct | ●Compr.

Discusion

- Well tempering uses co-annihilation of electroweakinos to set the observed relic abundance
  - Does not have to be supersymmetric
- Small mass splittings result
- Weak LHC limits (hard to trigger)
- Searching for soft objects recoiling off hard jet allow for collider coverage of most of the surface

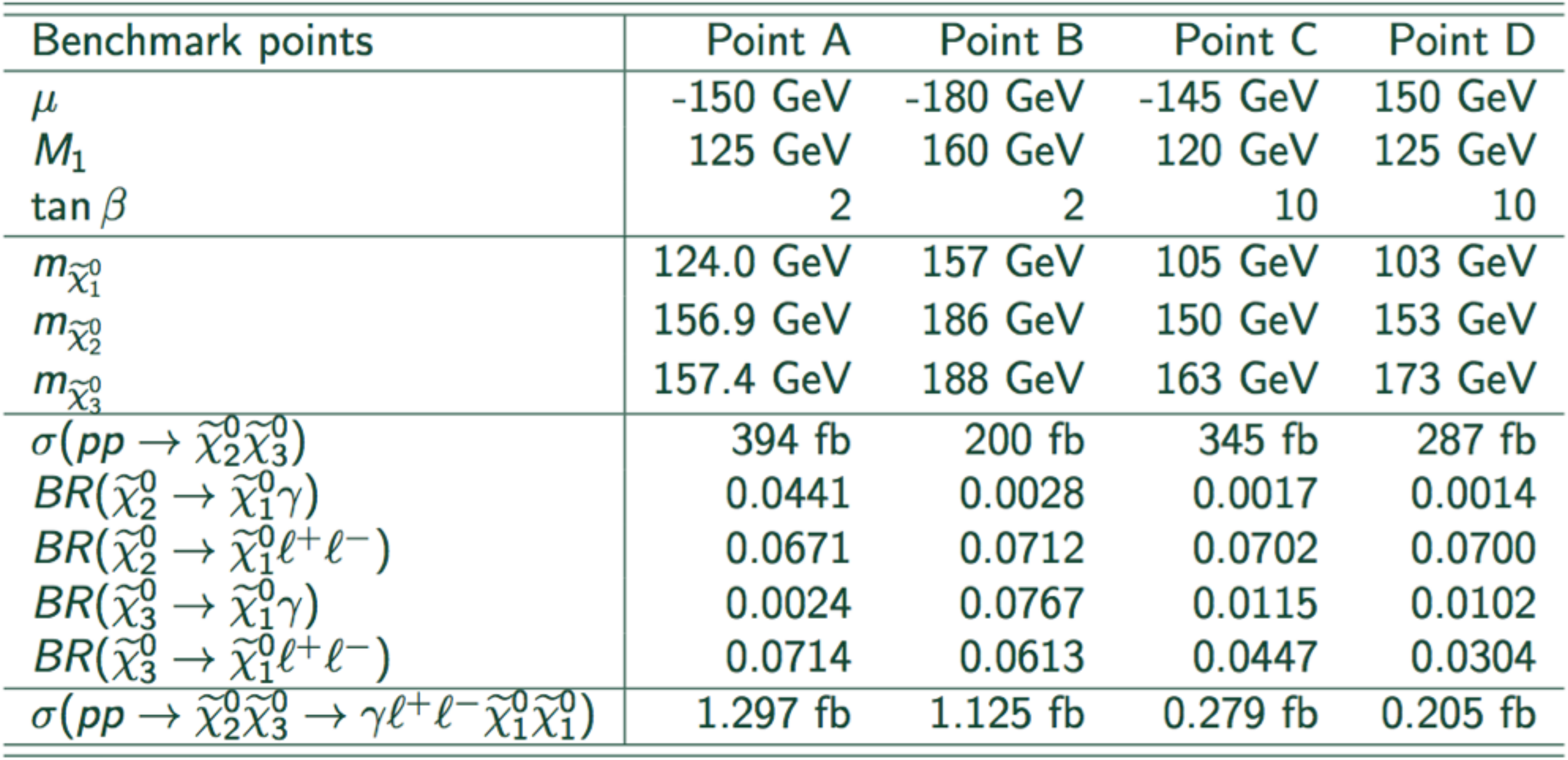


- A few holes remain
- `Pure Higgsino' needs much more decoupled Wino and Bino

Questions?

- J. Bramante, N. Desai, P. Fox, A. Martin, BO and T. Plehn, "Towards the Final Word on Neutralino Dark Matter," arXiv:1510.03460 [hep-ph].
- J. Bramante, P. J. Fox, A. Martin, BO, T. Plehn, T. Schell and M. Takeuchi, "Relic neutralino surface at a 100 TeV collider," Phys. Rev. D **91**, 054015 (2015) dos:10.1103/PhysRevD.91.054015 [arXiv:1412.4789 [hep-ph]].
- J. Bramante, A. Delgado, F. Elahi, A. Martin and BO, "Catching sparks from well-forged neutrinos," Phys. Rev. D **90**, no. 9, 095008 (2014) dos:10.1103/PhysRevD.90.095008 [arXiv:1408.6530 [hep-ph]].

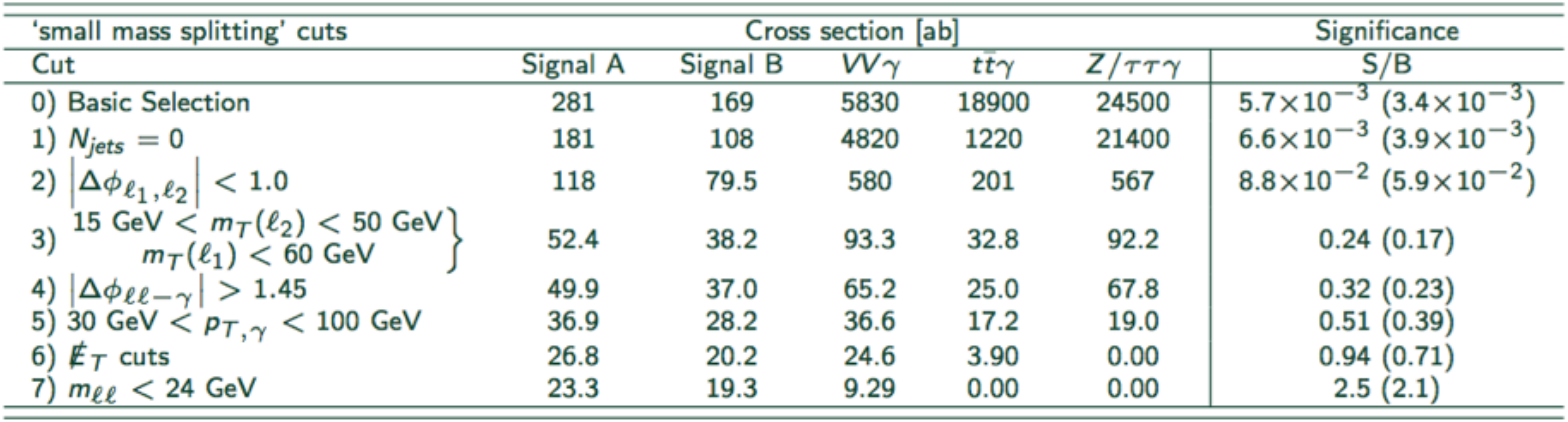
Back Up



Benchmark points	Point A	Point B	Point C	Point D
μ	-150 GeV	-180 GeV	-145 GeV	150 GeV
M_1	125 GeV	160 GeV	120 GeV	125 GeV
$\tan\beta$	2	2	10	10
$m_{\tilde{\chi}_1^0}$	124.0 GeV	157 GeV	105 GeV	103 GeV
$m_{\tilde{\chi}_2^0}$	156.9 GeV	186 GeV	150 GeV	153 GeV
$m_{\tilde{\chi}_3^0}$	157.4 GeV	188 GeV	163 GeV	173 GeV
$\sigma(pp \to \tilde{\chi}_2^0 \tilde{\chi}_3^0)$	394 fb	200 fb	345 fb	287 fb
$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma)$	0.0441	0.0028	0.0017	0.0014
$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-)$	0.0671	0.0712	0.0702	0.0700
$BR(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 \gamma)$	0.0024	0.0767	0.0115	0.0102
$BR(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-)$	0.0714	0.0613	0.0447	0.0304
$\sigma(pp \to \tilde{\chi}_2^0 \tilde{\chi}_3^0 \to \gamma \ell^+ \ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	1.297 fb	1.125 fb	0.279 fb	0.205 fb

Back Up

- Scan over all possibilities for each cut (not $m_{\ell\ell}$)
- Pick cut which maximizes $S/\sqrt{B}$
- Repeat until no gain in significance or each cut has been used

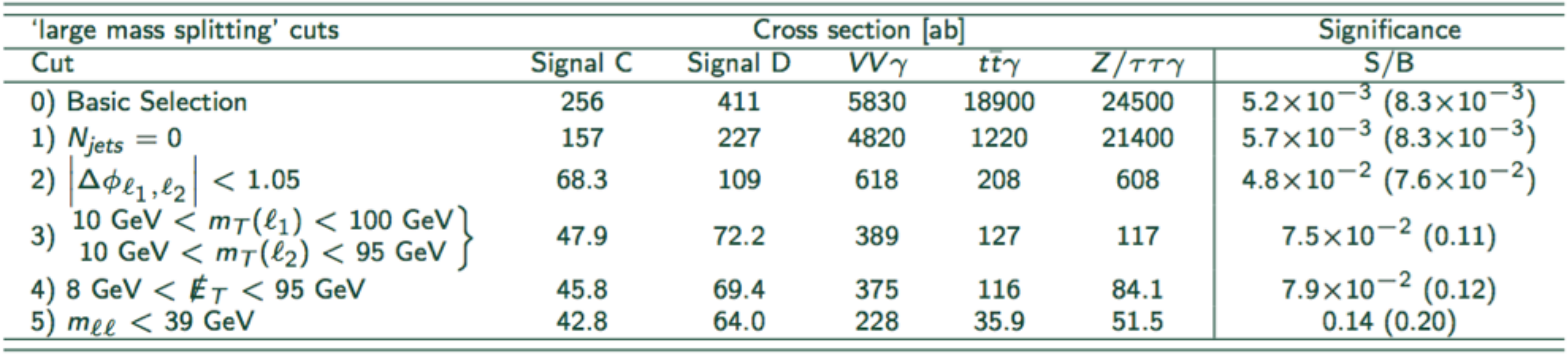


'small mass splitting' cuts		Cross section [ab]				Significance
Cut	Signal A	Signal B	$VV\gamma$	$t\bar{t}\gamma$	$Z/\tau\tau\gamma$	S/B
0) Basic Selection	281	169	5830	18900	24500	5.7×10^{-3} (3.4×10^{-3})
1) $N_{jets} = 0$	181	108	4820	1220	21400	6.6×10^{-3} (3.9×10^{-3})
2) $\left\|\Delta\phi_{\ell_1,\ell_2}\right\| < 1.0$	118	79.5	580	201	567	8.8×10^{-2} (5.9×10^{-2})
3) $\left.\begin{array}{c} 15\text{ GeV} < m_T(\ell_2) < 50\text{ GeV} \\ m_T(\ell_1) < 60\text{ GeV} \end{array}\right\}$	52.4	38.2	93.3	32.8	92.2	0.24 (0.17)
4) $\left\|\Delta\phi_{\ell\ell-\gamma}\right\| > 1.45$	49.9	37.0	65.2	25.0	67.8	0.32 (0.23)
5) $30\text{ GeV} < p_{T,\gamma} < 100\text{ GeV}$	36.9	28.2	36.6	17.2	19.0	0.51 (0.39)
6) $\not{E}_T$ cuts	26.8	20.2	24.6	3.90	0.00	0.94 (0.71)
7) $m_{\ell\ell} < 24$ GeV	23.3	19.3	9.29	0.00	0.00	2.5 (2.1)

- Discover 'A' with 430 fb^{-1} (125 GeV DM particle)
- Discover 'B' with 620 fb^{-1} (157 GeV DM particle)

Back Up

- Points ‘C’ and ‘D’ have larger mass splittings
- Cuts not as effective
- More possibility of ‘Alternative Signal’



‘large mass splitting’ cuts	Cross section [ab]					Significance
Cut	Signal C	Signal D	$VV\gamma$	$t\bar{t}\gamma$	$Z/\tau\tau\gamma$	S/B
0) Basic Selection	256	411	5830	18900	24500	5.2×10^{-3} (8.3×10^{-3})
1) $N_{jets} = 0$	157	227	4820	1220	21400	5.7×10^{-3} (8.3×10^{-3})
2) $\left\lvert\Delta\phi_{\ell_1,\ell_2}\right\rvert < 1.05$	68.3	109	618	208	608	4.8×10^{-2} (7.6×10^{-2})
3) $\left.\begin{matrix}10\text{ GeV} < m_T(\ell_1) < 100\text{ GeV}\\ 10\text{ GeV} < m_T(\ell_2) < 95\text{ GeV}\end{matrix}\right\}$	47.9	72.2	389	127	117	7.5×10^{-2} (0.11)
4) 8 GeV $< \not{E}_T <$ 95 GeV	45.8	69.4	375	116	84.1	7.9×10^{-2} (0.12)
5) $m_{\ell\ell} <$ 39 GeV	42.8	64.0	228	35.9	51.5	0.14 (0.20)

- Discover ‘C’ with 4300 fb^{-1} (105 GeV DM particle)
- Discover ‘D’ with 1900 fb^{-1} (103 GeV DM particle)